A MAGNETIC DIRECT-CURRENT AMPLIFIER

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A MAGNETIC DIRECT-CURRENT AMPLIFIER

by

James P. Jamieson

AN ESSAY

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ABSTRACT

The purpose of this essay is to investigate the basic theory and operation of magnetic amplifiers, and to construct and obtain the characteristics of various one stage magnetic amplifiers, utilizing very small d-c control currents. The amplifier circuits tested include the series circuit with and without feedback, the biased amplifier circuit, and parallel circuit with self-saturation: characteristic curves were obtained for supply voltage frequencies of 60 cycles per second and 400 cycles per second. The highest power gain obtained at 60 cycles per second was 1.12×10^6, and at 400 cycles per second was 37.1×10^6. The d-c control currents were in the microampere region.

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CHAPTER I

BASIC THEORY

History

The magnetic amplifier was patented in the United States by Mr. E. F. W. Alexanderson of the General Electric Company in 1916 for use as an audio frequency modulator of high frequency currents for radio telephony. The magnetic amplifier became of minor importance in this country, however, because the development of efficient dry disk rectifiers and high-permeability magnetic core materials, both necessary to the design of efficient magnetic amplifiers, came later than the popular employment of the vacuum tube. By the time these components were available, we had apparently forgotten the magnetic amplifier, while the Germans pursued its development for power applications. The successful use of the magnetic amplifier throughout the German Navy for ten years has demonstrated its efficiency, practicability, and resistance to failures due to shock and vibration. Its ruggedness was demonstrated when a mine, utilising a magnetic amplifier, was dropped from an airplane, and hit the rocky beach instead of the water. It was split wide open, but when the magnetic amplifier was recovered and tested, it was found to function perfectly.

In recent years, dry disk rectifiers of the selenium or copper oxide type have provided a convenient means for rectification of the load current to obtain d-c output and high sensitivity by positive feedback. Another important development has been the production of magnetic materials of high maximum permeability so that sat-

uration of the core requires less excitation.

General Properties

A magnetic amplifier is a power amplifying system securing its control properties from the saturation of high permeability magnetic cores called reactors. It consists essentially of a dry disk rectifier, if feedback is used, and two saturable core reactors, in which the degree of magnetization and flux change is controlled by auxiliary windings. There are no contacts, moving parts, filaments, or other features which make it liable to operating failure, or which necessitate constant inspection and maintenance. It can be made much more rugged and reliable than a vacuum tube amplifier, and its life span is indefinite.

One of the greatest advantages of the magnetic amplifier, in addition to its ruggedness, is the complete isolation of input and output loads. Since it is a power operated device, the impedance of the signal (control) source should match that of the control winding for optimum performance, and the load should be matched to the amplifier.

Similarity of the Magnetic Amplifier and Triode

A comparison of the magnetic amplifier with a triode is valid in some respects. The control windings correspond to the triode grid, and the power supply, a-c windings, and load correspond to the plate circuit. It must be noted, however, that the magnetic amplifier is a current operated device; a direct current applied to the control winding changes the a-c impedance of another winding. The vacuum tube may be considered to be a variable resistance in a d-c circuit, and a magnetic amplifier a variable inductive impedance

in an a-c circuit. In either case, a small control signal is used to vary a larger value of current or power in the load circuit. The similarity between electronic and magnetic amplifiers is indicated in Figure 1.

Series Circuit Without Feedback

Figure 2 shows a basic magnetic amplifier circuit. It is a series circuit without feedback. The a-c circuit consists of the cores, a-c voltage supply, and load. The control circuit consists of the control windings, connected in series opposing so that no fundamental component of the a-c supply voltage appears at the terminals of the control circuit.

In the discussion that follows, any resistance in the a-c winding is lumped with the load resistance, which approximation causes little error. Thus the drop across the reactor is considered purely inductive.

The manner in which a magnetic amplifier controls the output power is most readily seen by considering the a-c winding of the reactor as a variable impedance which can be changed at will from a high value to a lower value. This variation is achieved by passing direct current through the control winding, which increases the magnetic saturation of the core material on which the two windings are wound; this decreases the effective reactance of the a-c winding, allowing an increase in the output current flowing through the load resistance, the output current being a-c derived from the a-c source. Since the resultant change in power dissipated in the load can be considerably greater than the power causing the control current to flow, the device can be designated an amplifier.

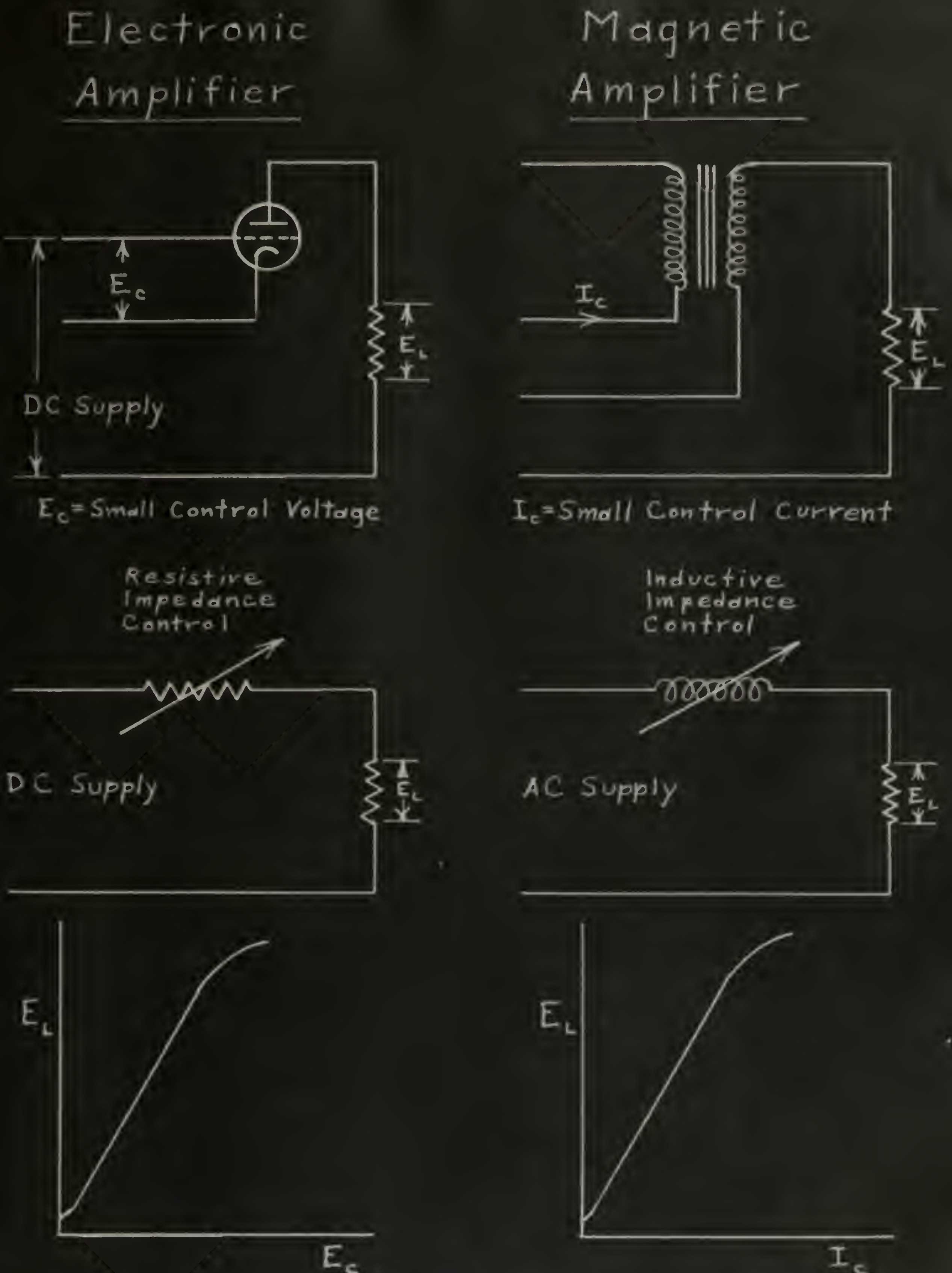
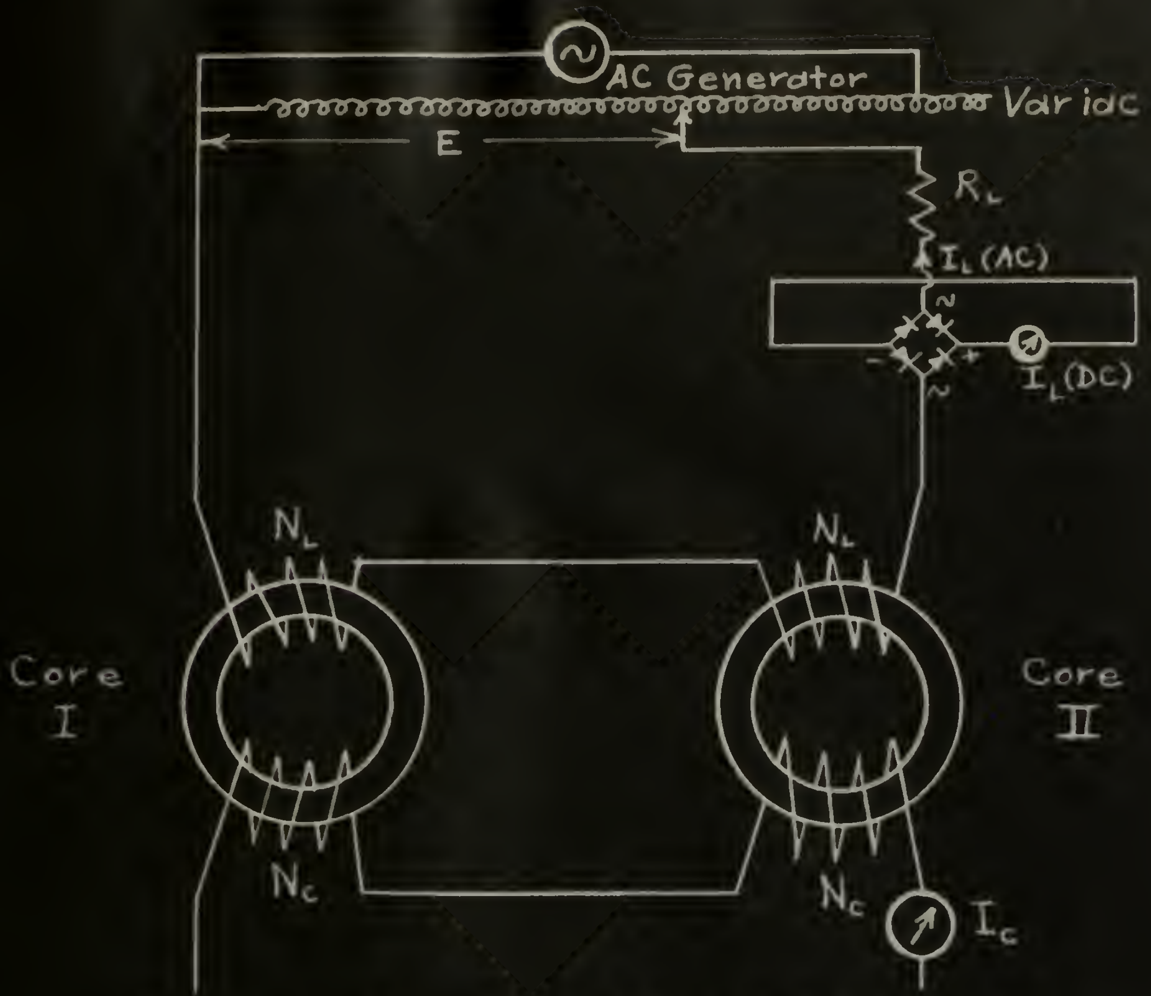
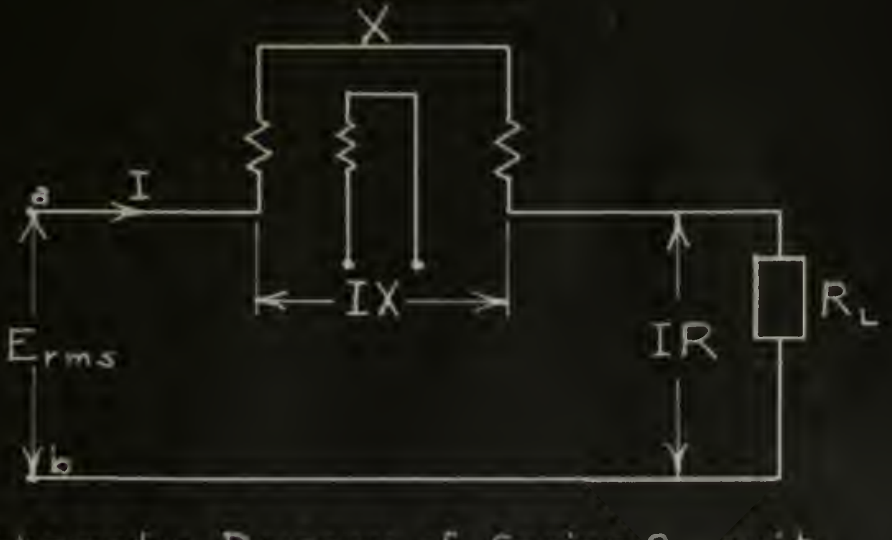

Electronic Amplifier
Magnetic Amplifier
E_c
DC Supply
E_L
I_c
E_L
E_c=Small Control Voltage
I_c=Small Control Current
Resistive Impedance Control
Inductive Impedance Control
DC Supply
E_L
AC Supply
E_L
E_L
E_c
E_L
I_c

Figure 1



Series Circuit Without Feedback

Figure 2



Schematic Diagram of Series Circuit

Figure 3

Graphical Analysis of Magnetic Amplifiers

Magnetic circuits cannot be conveniently calculated strictly analytically because the characteristic curves of the core material can only be handled approximately, and with great difficulty, mathematically. Therefore a graphical method, using the characteristic curve diagram of the particular core material, is advantageous in describing the operation of the magnetic amplifier.

A typical characteristic curve for a magnetic core is shown in Figure 4. It will be convenient in the discussion that follows to use the characteristic curve as shown in Figure 5.

The axes in Figures 4 and 5 may be labled in electrical units as well as magnetic units by using these relations:

(1). When there is no d-c excitation, the reactor voltage drop is proportional to the alternating magnetic flux density in the reactor core.

$E_{reactor} = 4.44\ N_L f\ B\ A \times 10^{-8}$ volts $= K_1 B$, for a given core

where $N_L =$ a-c turns

$f =$ supply frequency

$A =$ cross sectional area.

(2). The magnetic field intensity in the reactor is proportional to the reactor (and therefore load) current.

$H = .495$ ampere turns per inch

$\therefore I_L = K_2 H$, for a given core.

Electrical units will now be used in discussing the magnetic characteristics of the cores.

When no direct current flows in the control windings, the

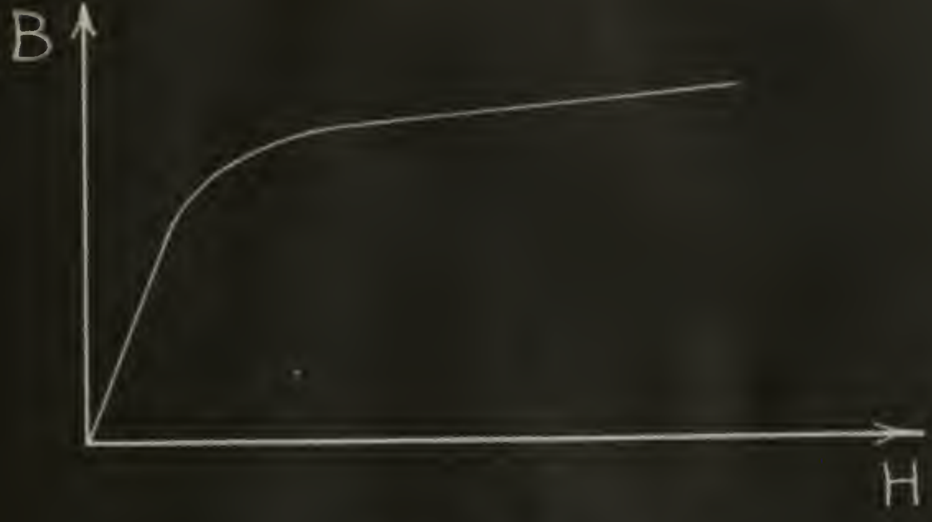


Figure 4

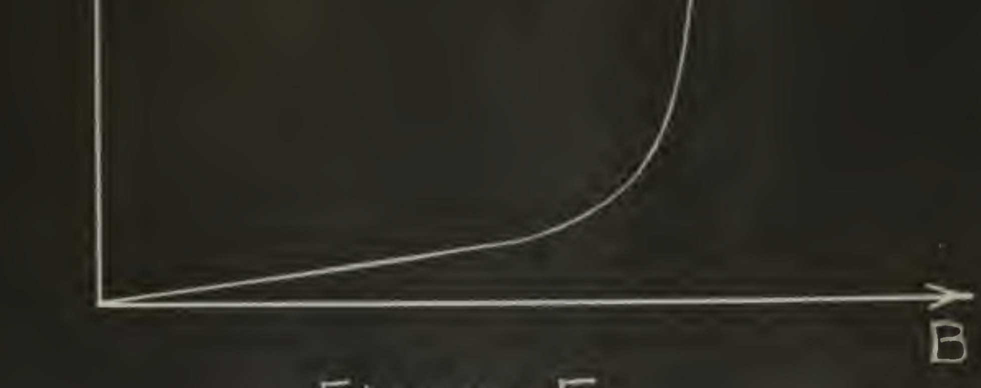


Figure 5

current I_L is determined entirely by the inductive reactance X_L of the a-c windings and the load resistance R_L. As R_L is very small compared to X_L, practically the entire supply voltage is across the a-c windings. If then the cores are subjected to an additional d-c magnetizing force, caused by a direct current I_C flowing in the control windings, X_L decreases, decreasing the total impedance of the a-c circuit, so that I_L increases. As I_C is further increased, X_L is decreased, and I_L increased to a greater value; but it is impossible to eliminate completely X_L, so the total supply voltage can never be transferal to R_L. The power absorbed by R_L is therefore regulated by I_C. The power amplification is the ratio of the change in $I_L^2 R_L$ to the change in d-c control power. The relation between the magnetizing current I_L and the supply voltage E, with control current I_C as a parameter, is shown by the family of curves for a particular magnetic material in Figure 6.

It is seen from Figure 6 that, for a given supply voltage E, the value of I_L increases as I_C is increased.

Impedance Diagram (8)

It is now desirable to consider the voltage drops in the a-c circuit. Figure 3 is a schematic diagram of the amplifier showing those voltages. The impedance diagram for this R-X circuit is shown in Figure 7.

When the value of reactance in series with the load resistance is varied, the locus of the a-c circuit impedance is as shown in Figure 7. For illustrative purposes, the figure is drawn for a tenfold change in the value of the reactance with minimum X set at 30% of load R. With X a minimum, the impedance is Z_{MIN}, and θ_{MIN} is 16.7°. For X_{MAX}, impedance is Z_{MAX}, and θ_{MAX} is about 71.6°.

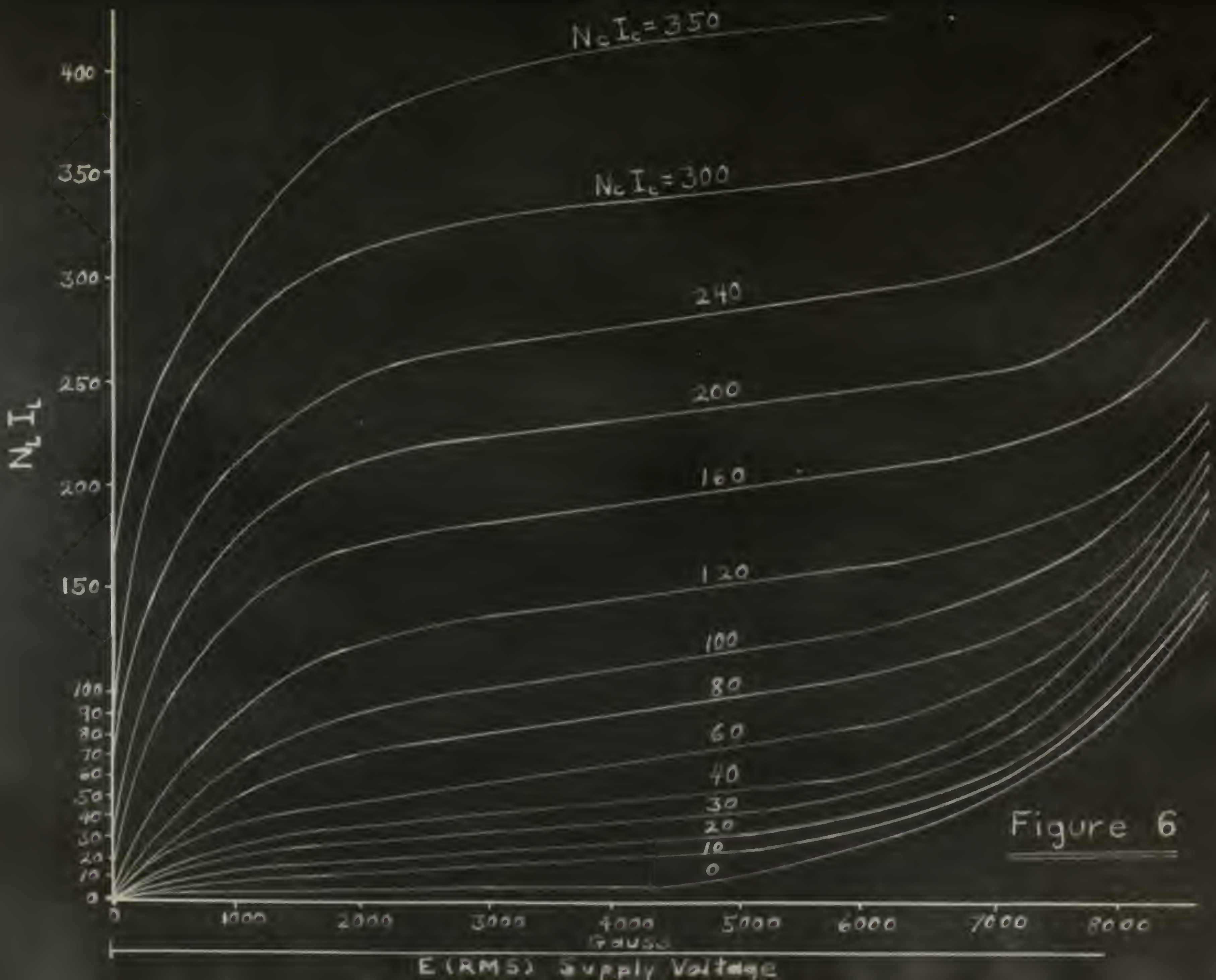


Figure 6

$N_c I_c = 350$
$N_c I_c = 300$
240
200
160
120
100
80
60
40
30
20
10
0
$N_L I_L$
400
350
300
250
200
150
100
90
80
70
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Gauss
E (RMS) Supply Voltage

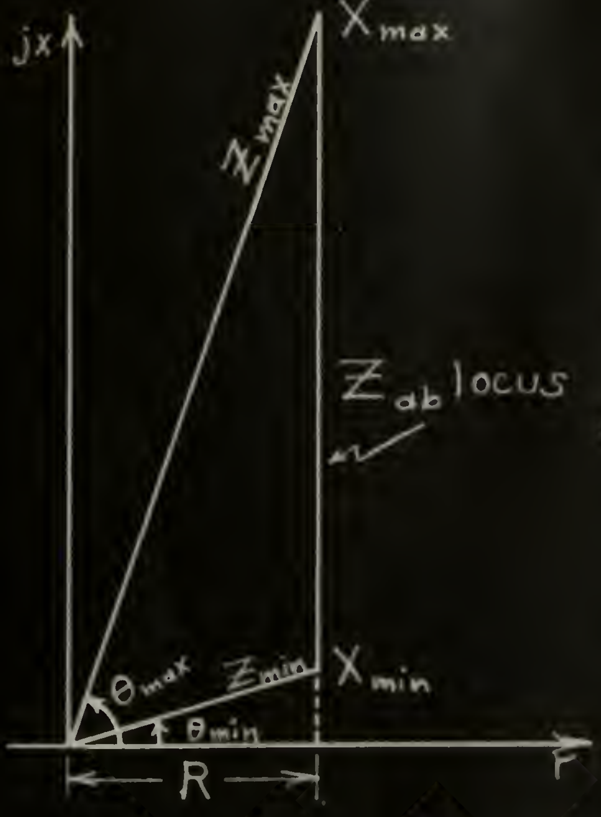


Figure 7

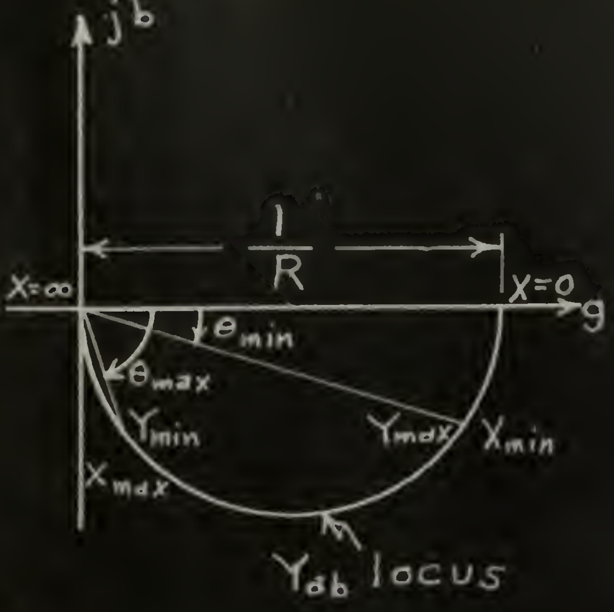


Figure 8

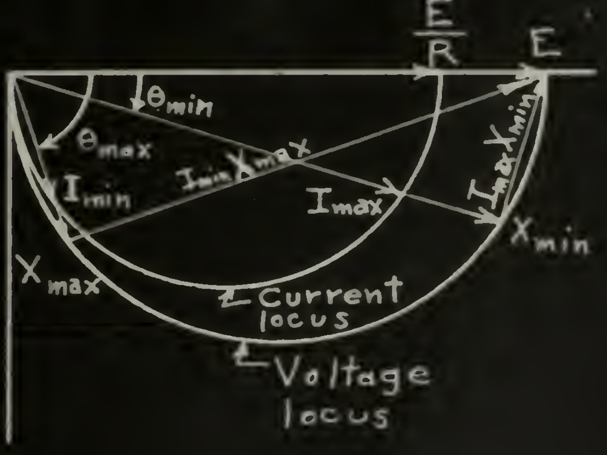


Figure 9

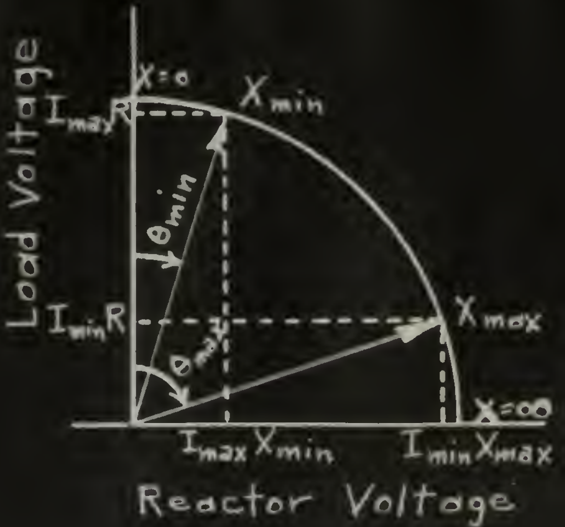


Figure 10

Admittance Locus (8)

The admittance locus corresponding to the impedance locus of Figure 7 is shown in Figure 8. Since the impedance locus is linear and the minimum impedance is R, the admittance locus is a circle with diameter equal to the reciprocal of the theoretical minimum impedance, or $\frac{1}{R}$. The current locus is derived by multiplying the admittance by supply voltage E. Thus when reactance has a minimum value, the admittance of the circuit has maximum actual value and maximum current flows. When the reactance has maximum value, admittance is a minimum, and a-c current is a minimum.

Current Locus (8)

The locus of the current in the a-c circuit is shown in Figure 9 as the smaller circle. Corresponding to the current locus of diameter E/R is the circular voltage locus having diameter E. The reactor and resistor voltages must add vectorially so that their sum is always equal to the applied voltage E. These vectorial additions are shown in Figure 9, and indicate the swing of voltage drops on reactor and load as the reactance of the saturable core device is adjusted.

Voltage Locus (8)

The voltage locus may be redrawn as shown in Figure 10. Again, the vectorial sum of resistor and reactor drops must equal the supply voltage, giving the circular supply voltage locus shown. Figure 10 shows that if the reactance were zero, the entire supply voltage would appear across the load. With any other value of circuit reactance, the supply voltage is divided as indicated by the

projections of the E vector on the reactor and load voltage axes. The figure shows that the actual limits of the circuit current are in the ratio of 3 to 1, while corresponding limits of the reactor voltage are in the ratio of 1 to 3.3; this gives a 10 to 1 reactance change for a 3 to 1 load current swing, which checks for the values used in this illustration. Figure 10 shows a reactor voltage scale and a load voltage scale, and a circular supply voltage locus relating the reactor voltage and load voltage. Since for a given load resistance, the value of load voltage corresponds directly with a load current, a change of scale can be made to make a circular locus of load current vs. reactor voltage. Since this is not convenient, the circle can be converted to an ellipse by changing one scale, in the following manner:

$E^2 = E^2_{reactor} + E^2_{load}$ is the equation of the circular locus.

But $E_{load} = I_{load} R_{load}$

So

$\frac{E^2_{reactor}}{E^2} + \frac{I^2_L}{\left(\frac{E}{R}\right)^2} = 1$, which is the equation of an ellipse.

This ellipse is an operating locus relating the reactor voltage with the reactor (or load) current.

For zero signal the line voltage is so adjusted that the maximum flux density in the cores is just at the knee of the magnetization curve. When a d-c signal is applied to the control windings, the cores are driven into saturation.

Operation of the Magnetic Amplifier(3)

The operation of the reactor is demonstrated by Figure 11, in which the plot of the circuit requirements is super-imposed on

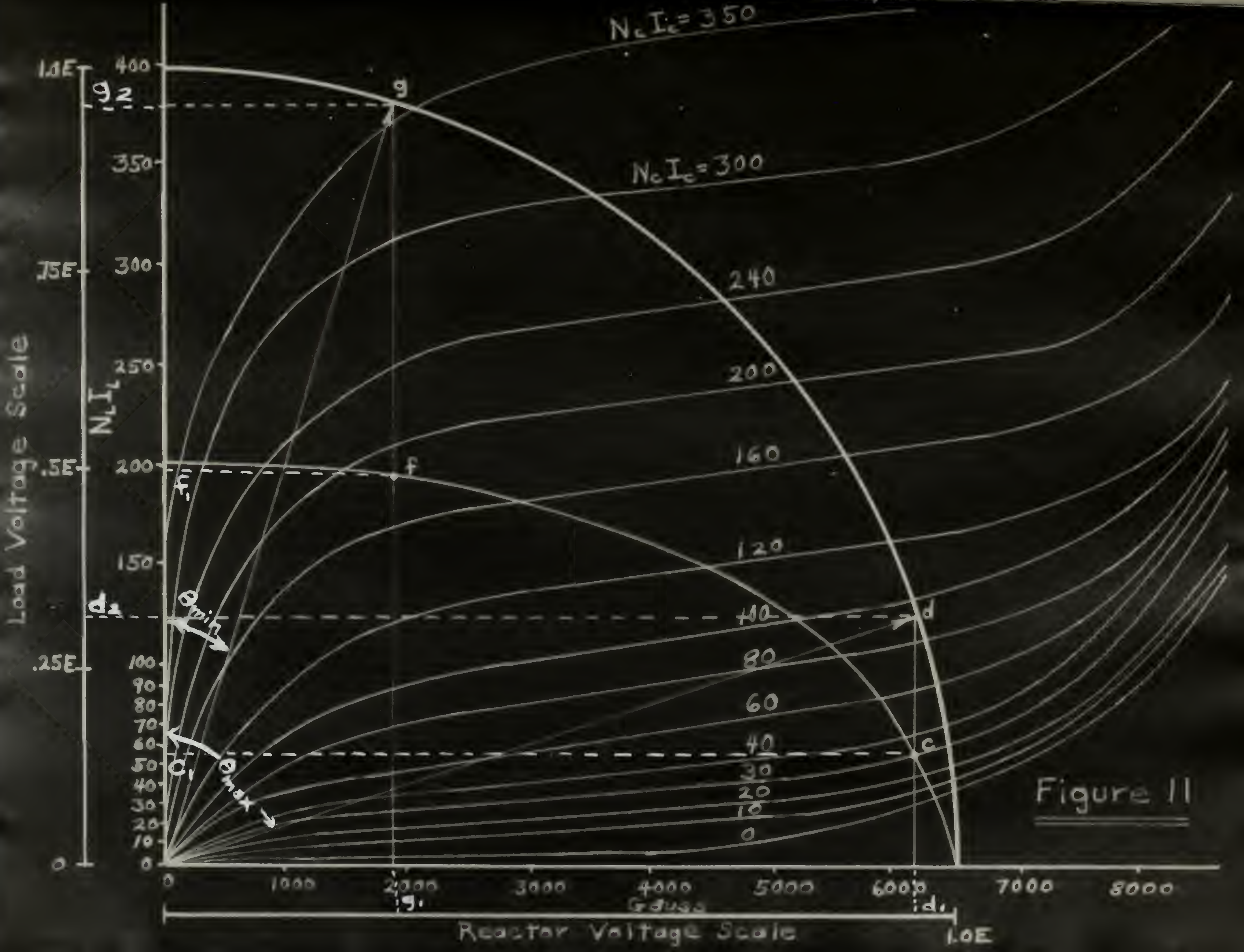


Figure 11

$N_c I_c = 350$
$N_c I_c = 300$
240
200
160
120
140
80
60
40
30
20
10
0
g
f
d
c
g_2
f_1
d_2
C_1
g_1
d_1
θ_{min}
θ_{max}
$N_L I_L$
Load Voltage Scale
1.0E
.75E
.5E
.25E
0
400
350
300
250
200
150
100
90
80
70
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Gauss
Reactor Voltage Scale
1.0E

the characteristic curve field of the core material. For the maximum impedance condition in the a-c circuit, corresponding to $Z_{MAX.}$ in Figure 10, the end of the voltage vector is located at point d, on the circular voltage locus. The voltage drop across the reactor is represented by Od_1 on the reactor voltage scale, and the drop across the load by Od_2 on the load voltage scale. Point c on the elliptical current locus corresponds to this position of the voltage vector, and shows that this maximum impedance condition occurs when $N_C I_C = 30$. Corresponding to this number of control ampere-turns is a value of $N_L I_L$ represented by Oc_1.

Point f on the operating current locus similarly corresponds to the voltage vector point g, and shows that $N_C I_C$ is about 185 for the minimum impedance case, giving $N_L I_L$ equal to the ordinate Of_1. Thus, for control between points c and f on the current operating locus, a difference of 185-30 or 155 ampere-turns is required. This corresponds, as has been indicated in the development of the circuit vector diagrams, to a 10 to 1 impedance change in the reactor and a 3 to 1 change in load current.

A diagram such as Figure 11 can be used to design circuits having various characteristics, but proper selection of core materials, size, and operating conditions require both experience and judgement.

Control Characteristics

The alteration of the rectified load current (I_L) as a function of the control current (I_C) is known as the control characteristic. This can be obtained from Figure 11, by considering points along the elliptical current operating locus. For example,

at point c, the value of $N_C I_C$ is 30; therefore $I_C = \frac{30}{N_C}$. Point c is projected on the vertical axis, and a value of $N_L I_L = 52$ is read; therefore $I_L = \frac{52}{N_L}$. Thus a value of I_L has been obtained for a value of I_C. Similarly, a value of I_L and I_C can be obtained for every point on the current operating locus. The control characteristic for the series circuit without feedback is symmetrical; Figure 12 is a typical curve for an amplifier in which the number of control turns is equal to the number of a-c turns. At zero control current there is a small initial current I_O, as the impedance of the a-c winding in this condition is high but not infinite. This is the exciting current. As the d-c signal is applied, the impedance decreases and I_L increases practically linearly at a slope $\frac{N_C}{N_L}$ (in this case 1). When the winding impedance becomes very low, the output current approaches a limit set by the applied a-c voltage and the total circuit resistance.

Series Circuit With Feedback

A series magnetic amplifier incorporating feedback effect is shown in Figure 13. With this arrangement, assuming 100% efficiency of rectifier, the full rectified output current is passed through the feedback windings N_F; thus the d-c magnetizing force is proportional to I_L. The percentage of feedback is given by the ratio $\frac{N_F}{N_L}$.

The control characteristic for a series connected feedback amplifier is shown in Figure 14.

From the ampere-turns balance law, for a series connected circuit, the total d-c ampere-turns required for the current I_L to flow is roughly $I_L N_L$. The feedback winding provides $I_L N_F$, and

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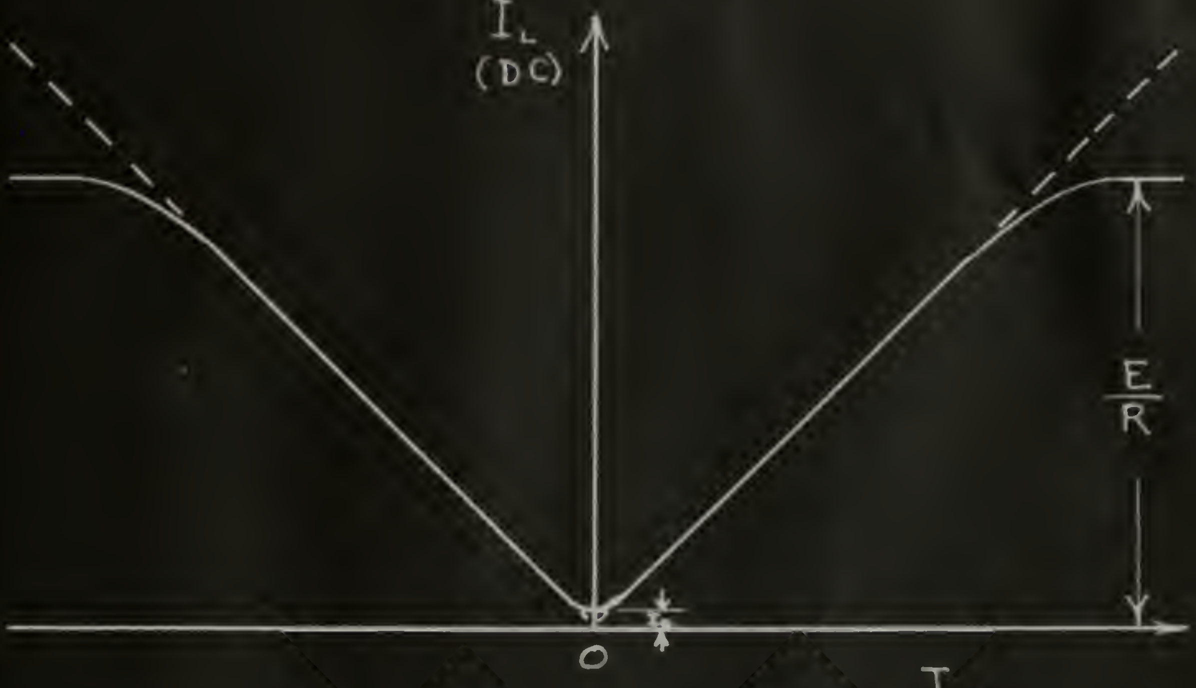
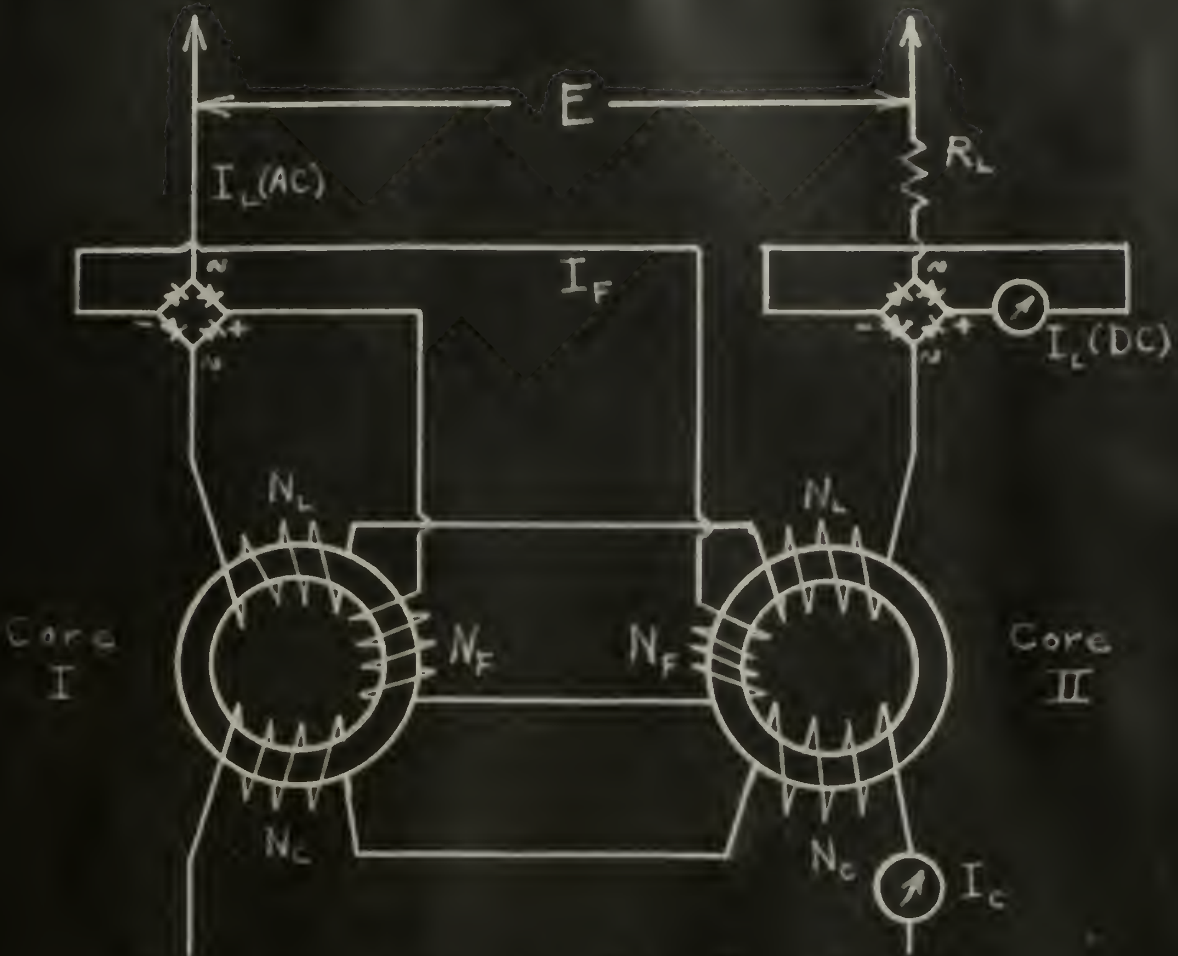
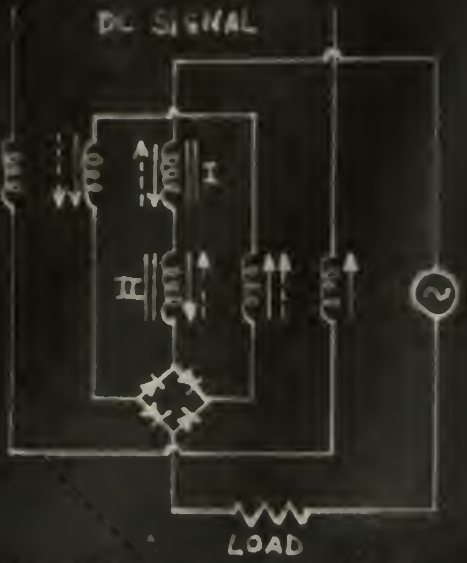


Control Characteristic

Figure 12



Series Circuit With Feedback



Schematic Diagram of Feedback Circuit

Figure 13

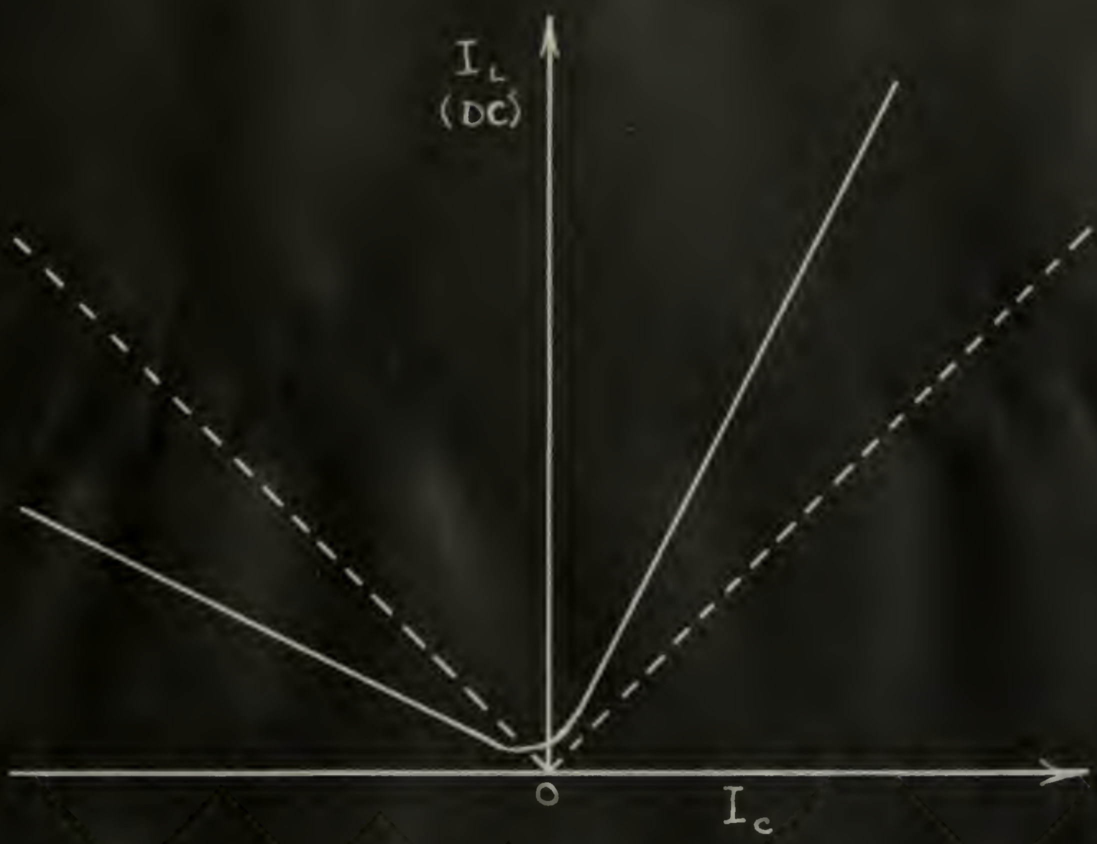


Figure 14

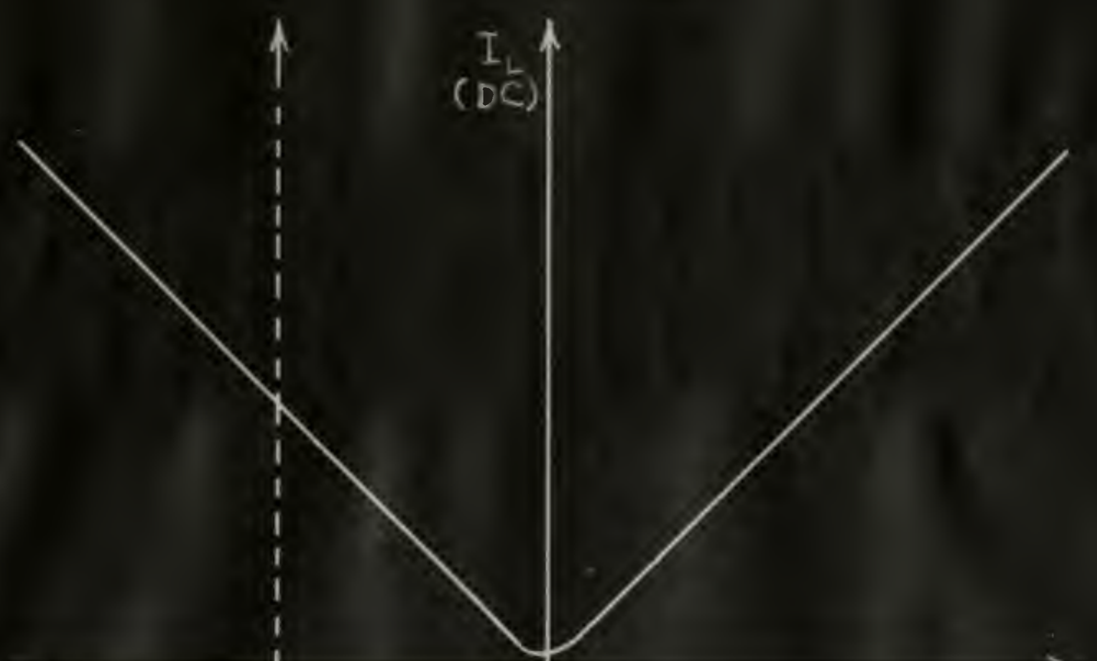


Figure 15

only the balance is supplied by the control winding. That is,

$$I_L N_L = I_L N_F \; I_C N_C$$

$$\therefore I_L = I_C \cdot \frac{N_C}{N_L} \left[\frac{1}{1 - \frac{N_F}{N_L}} \right]$$

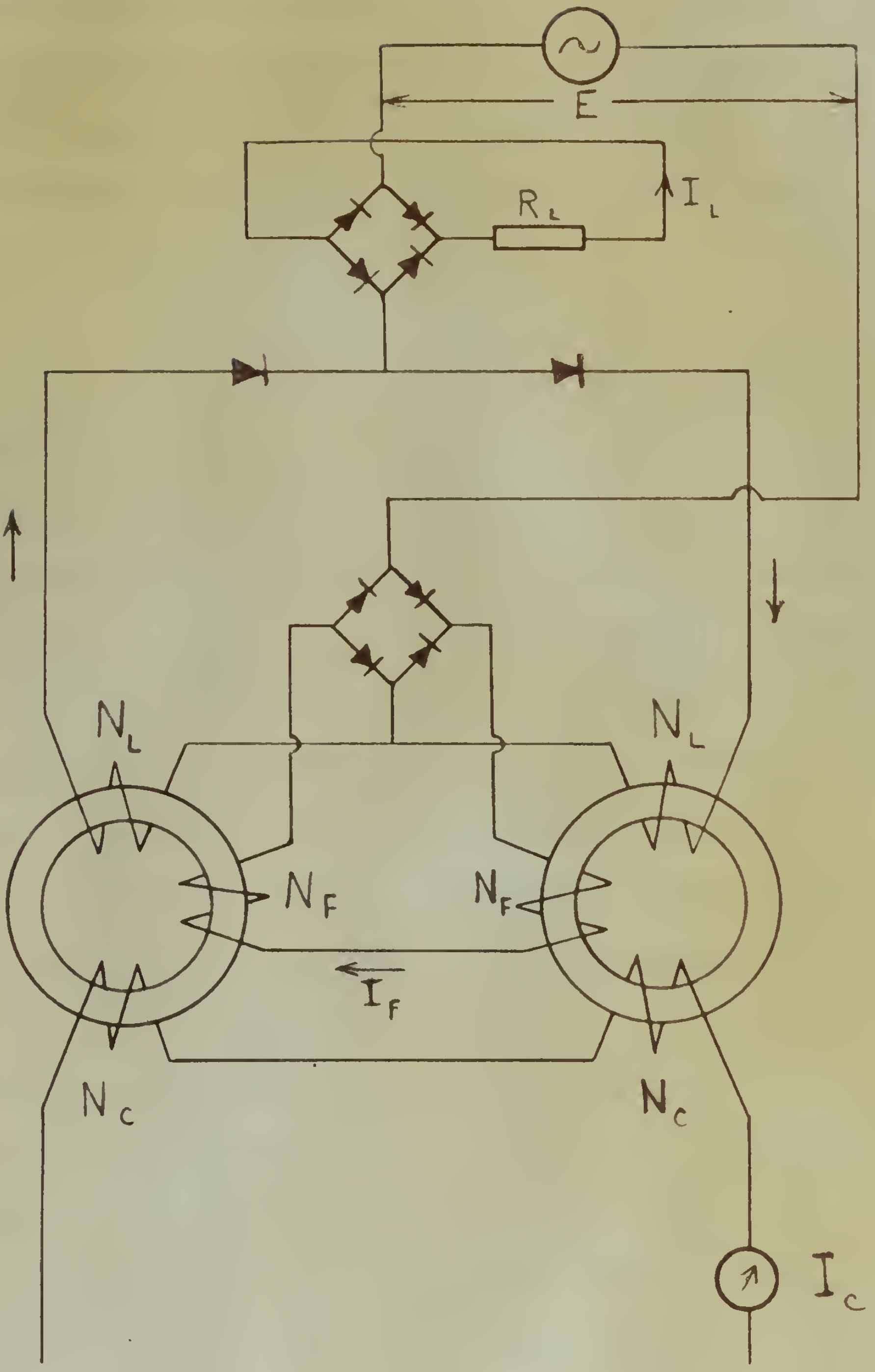
This gives an amplification which theoretically is infinite at 100% feedback. It holds, however, only for feedback up to approximately 97%. In actual practice, it is usually necessary to have N_F one or two turns greater than N_L for maximum amplification.

Biased Amplifier

By providing bias excitation from a separate source, the control characteristic can be made asymmetrical with respect to the zero control signal. The general shape of the characteristic is unchanged, but it is biased so that it crosses the $I_C = 0$ axis at about the center of the linear swing of I_L. Biasing shifts the position of the line $I_C = 0$ to any desired point, such as $0'$ in Figure 15, without affecting the shape of the characteristic curve. This allows the curve to be centered on the desired operating range.

Parallel Circuit with Self-Saturation (7)

Figure 16 shows a self-saturated circuit which obtains a form of positive feedback by connecting a half-wave rectifier in series with each load winding, so that the load current has a direct current component. This pulsating direct current in the load winding produces a d-c magnetization of the cores which is proportional to the average value of the load current I_L. The a-c windings in this circuit are connected in parallel; since the supply voltage is across each winding, the number of turns N_L must be double that of the series circuit.



Parallel Circuit With Self-Saturation

Figure 16

With no separate feedback windings, the circuit shown in Figure 16 corresponds to a series circuit with external feedback of 100%. Additional feedback turns N_F are added to vary the percentage of feedback effect. The current gain for this circuit is given by the relation:

$$\frac{I_L}{I_C} = 2\frac{N_c}{N_L} \cdot \frac{1}{1 - \frac{N_L - 2N_F}{N_L}}$$

Time Constant (1)(5)

If a d-c voltage of constant magnitude is suddenly applied to the control terminals of a magnetic amplifier, the control current lags behind the applied voltage due to the inductance of the control circuit. The time required for the output current to rise to 63% $(1 - \frac{1}{e})$ of its final value is the time constant of the amplifier, and is the ratio of the control coil inductance to its resistance. To obtain high gain, the core material must be readily saturated by the control signal, which results in a highly inductive input circuit, and a large time delay. For this reason high gain is usually associated with large time constants.

The presence of both a-c and d-c fluxes in the core makes the calculation of the d-c flux extremely tedious. However, an approximate method for calculating the inductance of the control coil can be developed by determining the average permeance of the iron path which is traversed by the a-c flux, which will illustrate the factors upon which the time constant is dependent.

Considering the voltage drop across the load winding at an average value of X_L, for an amplifier without feedback:

(1.) $e_{ave} = 2\pi fL_{a\text{-}c\ coil}\, I_{L_{DC}} = X_L\, I_{L_{DC}}$

Permeance, which is the reciprocal of the reluctance of a magnetic path, is the ratio of the magnetic flux in the core to the magnetomotive force producing it. It is closely related to self inductance, and in general, the ratio of self inductance to the permeance of an electro-magnetic system is proportional to the square of the number of turns carrying the current.

Therefore:

(2.) $L_{a\text{-}c\ \text{coil}} = N_L^2 \mathcal{P}_{a\text{-}c\ \text{flux path}}$

Substituting (1) in (2),

(3.) $2\pi f N_L^2 \mathcal{P}_{a\text{-}c} = X_L$

So (4.) $\mathcal{P}_{a\text{-}c} = \dfrac{X_L}{2\pi f N_L^2}$

Since the d-c flux traverses the same path in a toroidal coil as the a-c flux,

(5.) $\mathcal{P}_{a\text{-}c} = \mathcal{P}_{d\text{-}c}$

Since the inductance of the control circuit is

(6.) $$L_{d\text{-}c\ \text{coil}} = N_c^2 \mathcal{P}_{d\text{-}c} = \frac{X_L}{2\pi f}\left[\frac{N_c}{N_L}\right]^2 ,$$

the time constant of the control circuit is

(7.) $$T_{c_1} = \frac{L_{d\text{-}c}}{R_c} = \frac{X_L}{2\pi f R_c}\left[\frac{N_c}{N_L}\right]^2$$

H. S. Kirschbaum and E. L. Harder(5) have extended this calculation to derive an expression for the time constant of an amplifier with positive feedback, giving the result

(8.) $$T_{c_2} = \frac{\left[1 + \dfrac{R_c N_F^2}{R_F N_c^2}\right]}{\left[1 - \dfrac{K N_F}{R_F N_c}\right]} \cdot T_{c_1}$$

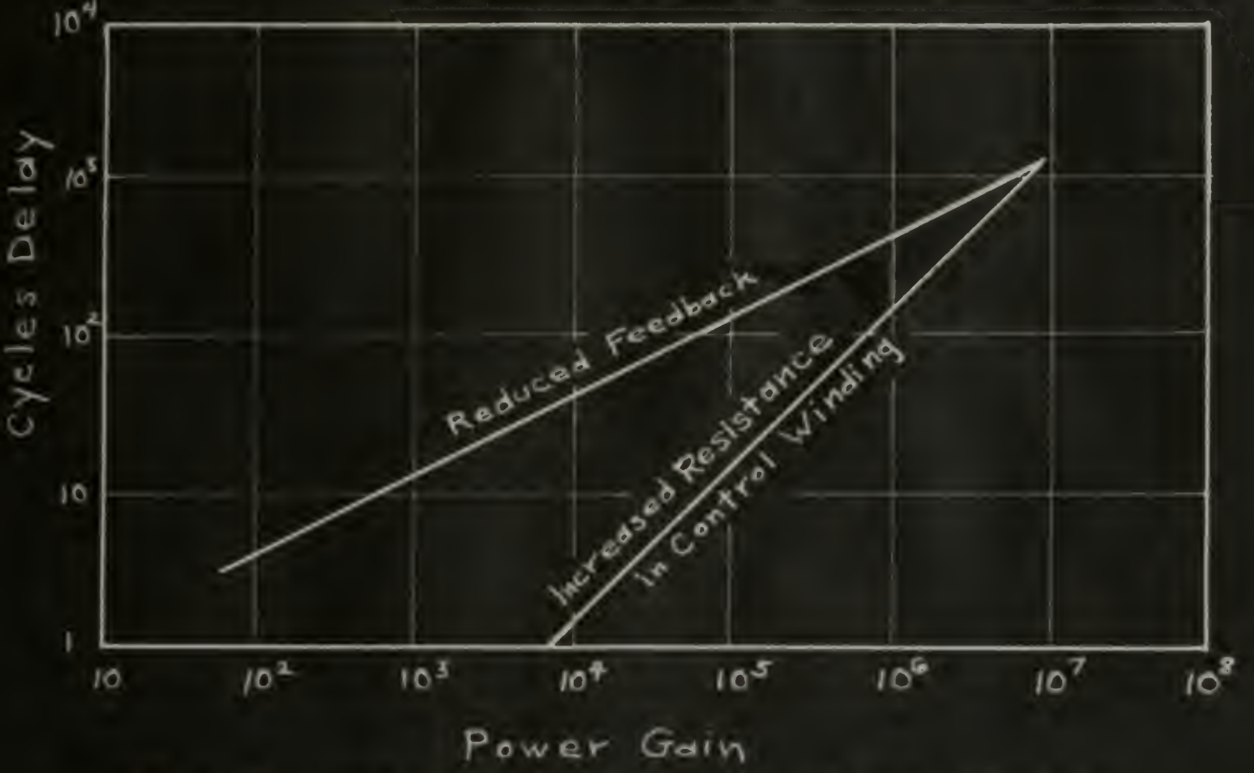
where K is a constant depending on the circuit parameters.

Equations (7) and (8) show that the time delay is inversely proportional to the supply frequency, f, and is increased when the number of feedback turns, N_F, is increased.

The fact that the time delay is inversely proportional to the frequency of the power source means that for a given gain, an amplifier operated at 60 cycles per second will have a time delay which is approximately 7 times the delay of the equivalent amplifier operated at 400 cycles per second. In other words, for any power frequency, the same number of cycles is required for the output to rise to 63% of its final value.

There are two methods for reducing the time constant of the feedback circuit, both of which reduce the gain. One method is to insert series resistance in the control winding circuit, thereby reducing the time constant $\left(\frac{L}{R}\right)$ of the control winding circuit, and the other is to reduce the amount of feedback. Figure 17 compares the results obtained by reducing the feedback with those obtained by increasing the resistance in the control circuit. It shows that if the gain is reduced by a factor of four by adding resistance in the control winding, the time delay is also reduced by a factor of four. If the gain is reduced by a factor of four by reducing the feedback, however, the delay is only reduced by a factor of two.

To summarize, the delay in cycles of power frequency is proportional to power gain, and independent of core material and power frequency. It is better to work from the maximum gain condition by adding R to the control circuit to cut the gain than to



Two Methods of Reducing Time Delay

Figure **17**

decrease feedback. For a given power gain, the recommended procedure is to utilize the maximum feedback commensurate with stability and add series resistance in the control winding until the desired gain-delay ratio is obtained. The actual time of response in seconds is improved by the use of a higher power frequency.

The cycles of delay for a certain power gain can be decreased by splitting the amplifier into two low gain stages.

Magnetic Materials(2)

Desirable features of magnetic cores for amplifier use are:

1. Steel should saturate at as low a magnetizing force as possible.
2. Steel should have a very sharp knee on the saturation curve and the knee should occur as near maximum flux density as possible. Any additional flux after passing the knee of the curve causes induced voltages which makes it impractical to obtain maximum voltage across the load.
3. Steel should have as high a flux density at saturation as possible. This permits the use of smaller cores for a required output voltage.
4. The steel should be consistent so that two or more cores which make up the amplifier will be similar for best performance, and various amplifiers made to the same specifications will have similar characteristics.
5. Steel losses should be small. Eddy currents not only cause power loss but also cause the amplifier to have slower response. Hysteresis losses in addition to

causing power losses may have an undesirable effect on the input-output characteristic of the amplifier; that is, the output power may be different depending on whether the control is increasing or decreasing.

Rectifiers

High quality rectifiers are essential in magnetic amplifiers. Desirable features are:

1. Low forward resistance, in order that power loss and voltage drop is kept to a minimum.
2. Very low back leakage; leakage increases the amount of control current required, resulting in an overall loss in power gain.
3. Very stable characteristics; any change in rectifier operating characteristics changes the performance of the magnetic amplifier in which it is used, especially if the rectifier develops leakage.

Advantages and Applications of Magnetic Amplifiers

The advantages of magnetic amplifiers are:

1. They require no power supply such as "B" supply for vacuum tubes. Although reactors weigh more than tubes, the size and weight of completed amplifiers can often be made equal to or less than vacuum tube amplifiers, since the power supply is eliminated.
2. They require no warm-up time.
3. They do not have the power limit of vacuum tubes.
4. Very high power amplification per stage is possible.

Magnetic amplifiers are not practical in many applications

which now use vacuum tubes. They do, however, have qualities and limitations which define their scope; they are a valuable addition to existing circuit techniques and are finding increasing application. The particular qualities of the magnetic amplifier are;

1. Amplification of low level d-c powers
2. Mixing of input signals which are at different voltage levels
3. Isolation of input and output
4. Good zero-stability
5. Ruggedness.

The present limitations of the magnetic amplifier are:

1. It is restricted to applications using a signal frequency that is low compared to the supply voltage frequency.
2. Long time constant
3. Limited impedance range
4. In some cases, the size and weight of the magnetic amplifier may be greater than that of a vacuum tube amplifier.

Conclusion

Magnetic amplifiers have found many industrial applications. Examples of their use are in voltage regulators, automatic battery chargers, theatre lighting control, servo amplifiers, and audio amplifiers (with high frequency power supply). They are especially suited for electrical control of military equipment; their service record is demonstrated by the statement of a technician on the German cruiser "Prinz Eugen", who claimed that not once to his know-

ledge during the ten years that he was on board were the panels of the magnetic amplifier units opened.

CHAPTER II

CONSTRUCTION OF EQUIPMENT

Object

The object of the experimental work was to design a magnetic amplifier to amplify very small d-c powers; the equipment was so constructed that various types of magnetic amplifier circuits can be readily assembled, and their characteristics obtained. In this form, the amplifier is also suitable for the demonstration of various magnetic amplifier circuits in the classroom or laboratory.

Magnetic Cores

The two cores used in this amplifier were supplied by the Magnetic Materials Group of the Naval Ordnance Laboratory. They are Mu Metal cores, made of tape .003 inches thick and one-half inch wide, wound into toroids of inside diameter one and five-eights inches and outside diameter two inches. The layers of tape are insulated by magnesium oxide. The cross-sectional area of the magnetic path in the cores is .557 $cm.^2$, and the mean length of the magnetic path is 14.464 cm. The two cores are very well matched, each having a maximum permeability of 226,561. The magnetization curves for these two cores are plotted in Figures 18 and 19.

Mu Metal is a high nickel magnetic alloy; its composition is 75% nickel, 2% chromium, 5% copper, and 18% iron. It has a high permeability, low coercive force, and low saturation flux density. Since it was intended to construct a magnetic amplifier to amplify very small currents, it was necessary to use a core

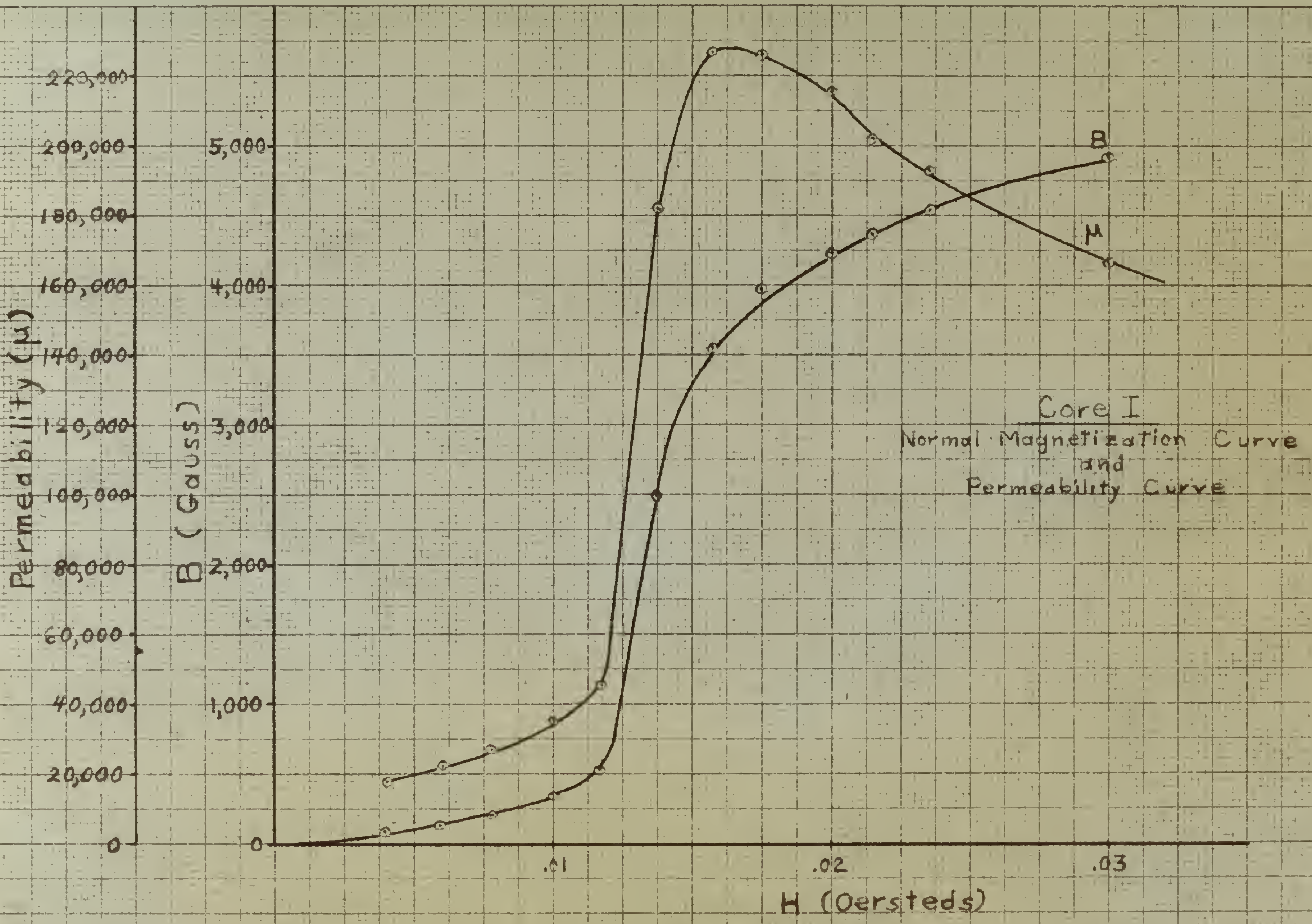

Core I
Normal Magnetization Curve
and
Permeability Curve
B
μ
Permeability (μ)
220,000
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
B (Gauss)
5,000
4,000
3,000
2,000
1,000
0
.01
.02
.03
H (Oersteds)

Figure 18

material with high permeability and low coercive force to keep the number of turns on the control winding from becoming excessive. Mu Metal has the high permeability required for large inductance and also requires relatively few ampere-turns to saturate it, thus providing a large change in impedance and a large power gain.

Heat Treatment

The Mu Metal cores were annealed at a relatively high temperature in a pure hydrogen atmosphere. These conditions not only prevent oxidation, but remove impurities from the charge. Commercial electrolytic hydrogen is used at NOL, and it is further purified by removing oxygen and moisture until the oxygen content is below one part per million, and the moisture content of the purified gas as measured by dew-point determination is below -90° F. The cores were annealed in an open tray in the hydrogen atmosphere for four hours at a temperature of 1200° C.

Winding Coils on Cores

It is well known that the magnetic properties of high permeability materials are adversely affected by mechanical strains. It has been found, however, that by proper mounting, magnetic amplifiers can be constructed that will withstand severe shock and vibration.

The method used in the amplifier being described consisted of placing each toroidal core in a molded bakelite box, large enough to permit a small motion of the core. This prevents strain from being placed on the core material by the box or the windings. The coils were then wound around the bakelite box by a toroidal

winding machine, and the last few coils wound by hand. The winding machine was located at the Naval Ordnance Laboratory, and the author received sufficient instruction in its use to wind the coils. The following separate coils were wound with #27 AWG wire on each core:

11 coils —— 400 turns
1 coil —— 200 turns
1 coil —— 100 turns
1 coil —— 50 turns
1 coil —— 20 turns
1 coil —— 10 turns
1 coil —— 5 turns
2 coils —— 1 turn

Thus, a total of 4787 turns were available on each core, wound in small coils so that any desired combination of turns for control, power, bias, and feedback windings could be obtained by making the necessary external connections.

The two cores were mounted on a board, and the coil ends attached to Jones strips, to facilitate making changes in the winding combinations.

Rectifiers

Selenium dry-disk rectifiers were used in this amplifier as they provide the ruggedness, reliability, and long life required of rectifiers for magnetic amplifier use. The rectifier is an aluminum base plate coated with selenium over which an alloy is sprayed. The aluminum base plate serves as one electrode and the alloy as the other. Current flows readily from the base plate to the alloy layer but only with extreme difficulty in the other direction. The high resistance to flow from the alloy to the base plate is called "reverse resistance", while the low resistance in the opposite direction is the

forward resistance. Thus each plate is a half wave rectifier. The rectifiers used in the circuits described in this essay were four units of three plates each, manufactured by the Radio Receptor Company.

Complete Assembly

A photograph of the equipment assembled for test is shown in Figure 20.

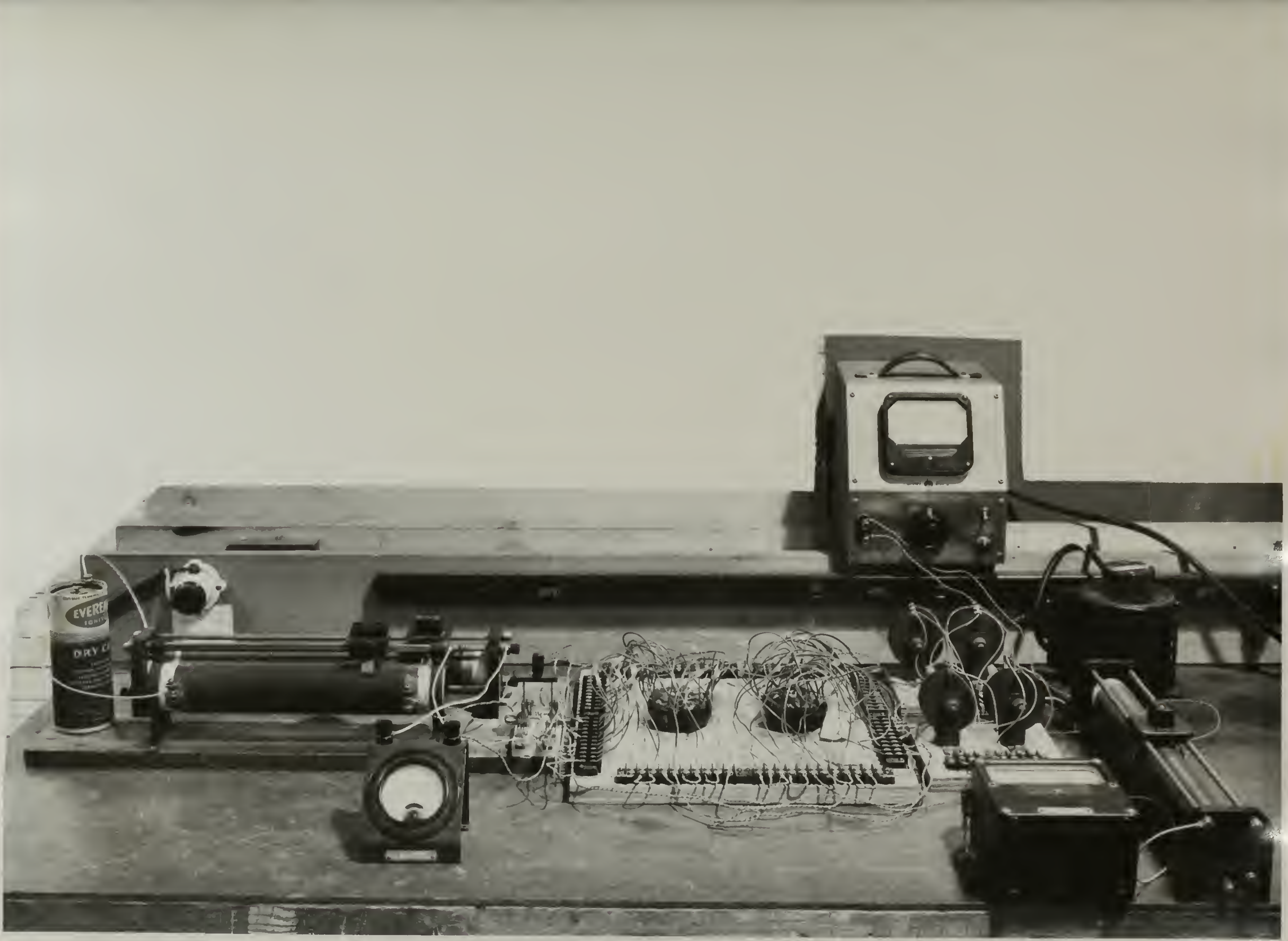


Figure 20

CHAPTER III

EXPERIMENTAL RESULTS

Tests were conducted to determine the characteristics of various magnetic amplifier circuits at supply frequencies of 60 cycles per second and 400 cycles per second. These two frequencies were used because they were readily available in the laboratory. The results obtained are presented in this section.

Tests Using 60 Cycles Per Second Supply Frequency

Determination of A-C Supply Voltage

The first step in the experiment was to determine the proper a-c supply voltage to be used. The circuit used was the series circuit without feedback, shown in Figure 3, with $N_C = N_L = 1200$ turns on each core. The load resistance was 50 ohms. The variation of output current with supply voltage was measured for various values of control current; the curves obtained are plotted in Figure 21, and show that within a large voltage range the load current is independent of the voltage, and equal to the control current, if the load and control windings have an equal number of turns. This illustrates the current transformer character of the magnetic amplifier.

The desired value of a-c voltage is achieved by adjusting the line voltage with zero control current so that the maximum flux density in the cores is just at the knee of the magnetization curve. This voltage is the one at which the plot of I_L vs. E, with $I_C = 0$ in Figure 21, begins to bend upward. With this value of applied voltage the core saturates on some portion of the supply cycle. As the con-

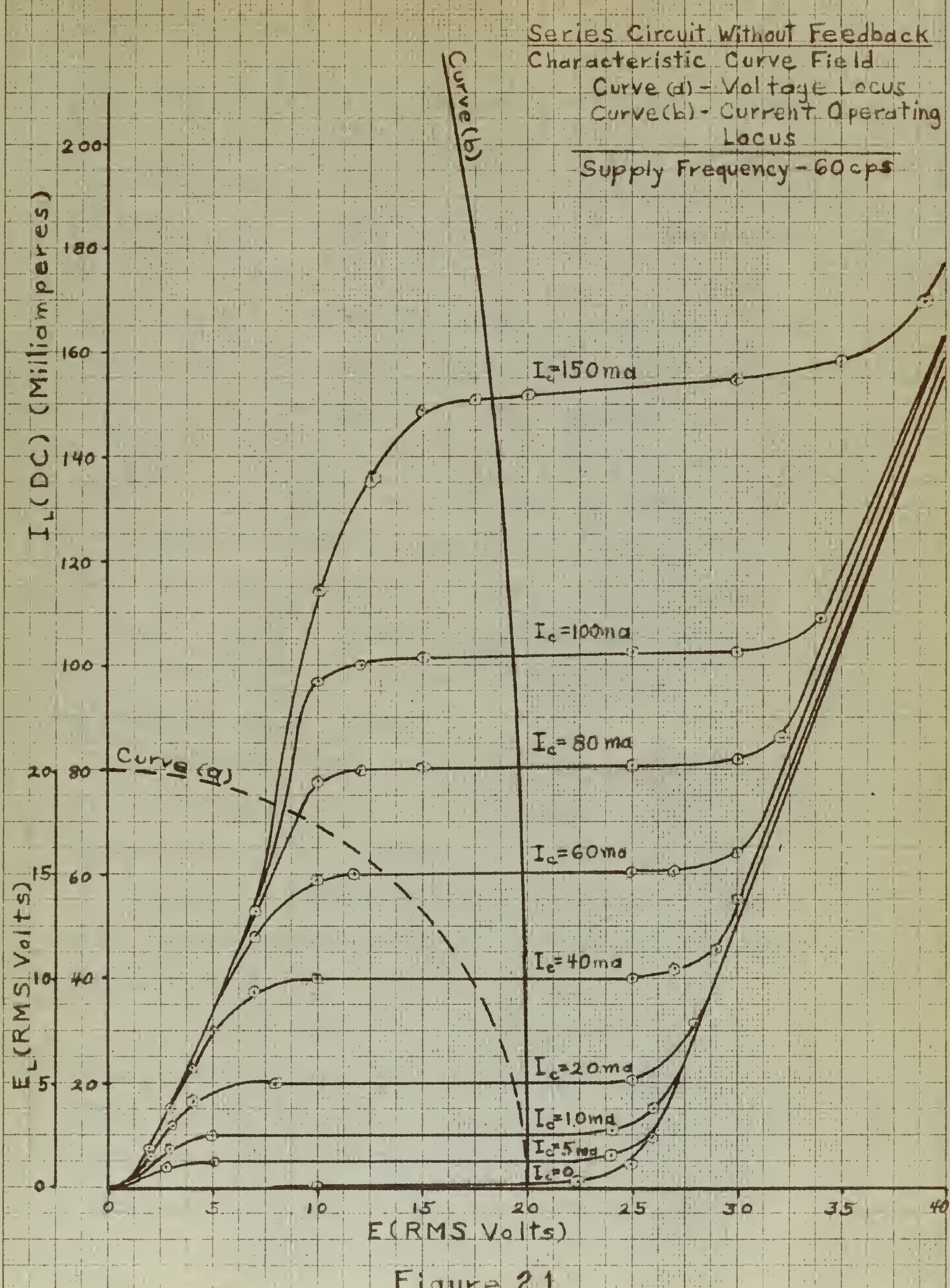

Series Circuit Without Feedback
Characteristic Curve Field
Curve (a) - Voltage Locus
Curve (b) - Current Operating Locus
Supply Frequency - 60 cps
Curve (b)
Curve (a)
I_c=150ma
I_c=100ma
I_c= 80 ma
I_c=60ma
I_c=40ma
I_c=20ma
I_c=1.0ma
I_c=.5ma
I_c=0
I_L (DC) (Milliamperes)
E_L (RMS Volts)
E (RMS Volts)
0
5
10
15
20
25
30
35
40
20
40
60
80
100
120
140
160
180
200

Figure 21

trol current is increased from zero, the current in the load windings is increased proportionally, until the cores are completely saturated. At this point the characteristic curve flattens out and a further increase of signal does not result in a further increase of the load current.

From Figure 21, it is determined that the desired operating a-c voltage is 20 volts (rms). Figure 21 is the characteristic curve field for the amplifier with Mu Metal cores and corresponds to Figure 11 in the basic theory section of this paper. The voltage locus has been superimposed on this field by drawing a circle (curve a) with its center at the origin, and passing through the point $E = 20$ volts. The elliptical current operating locus (curve b) was plotted using the relation $I_{L_{d-c}} = \frac{E_{rms}}{1.11R_L}$, and over the useful range is seen to be practically a straight line.

Series Circuit Without Feedback

The control characteristic curve discussed on page 13 is used in assessing the performance of the various circuits tested. Throughout this essay, the arithmetic mean value of the alternating load current is measured and plotted. I_L (DC) is measured across the d-c terminals of a full wave rectifier bridge, as shown in Figures 3 and 13.

Curve (a) of Figure 22 is the control characteristic for the series circuit without feedback, illustrated in Figure 3. The slope of the curve is equal to the theoretical value $\frac{N_C}{N_L} = 1$, and it is linear up to the limit of I_L, which is determined by the value of the applied voltage and the total load circuit resistance.

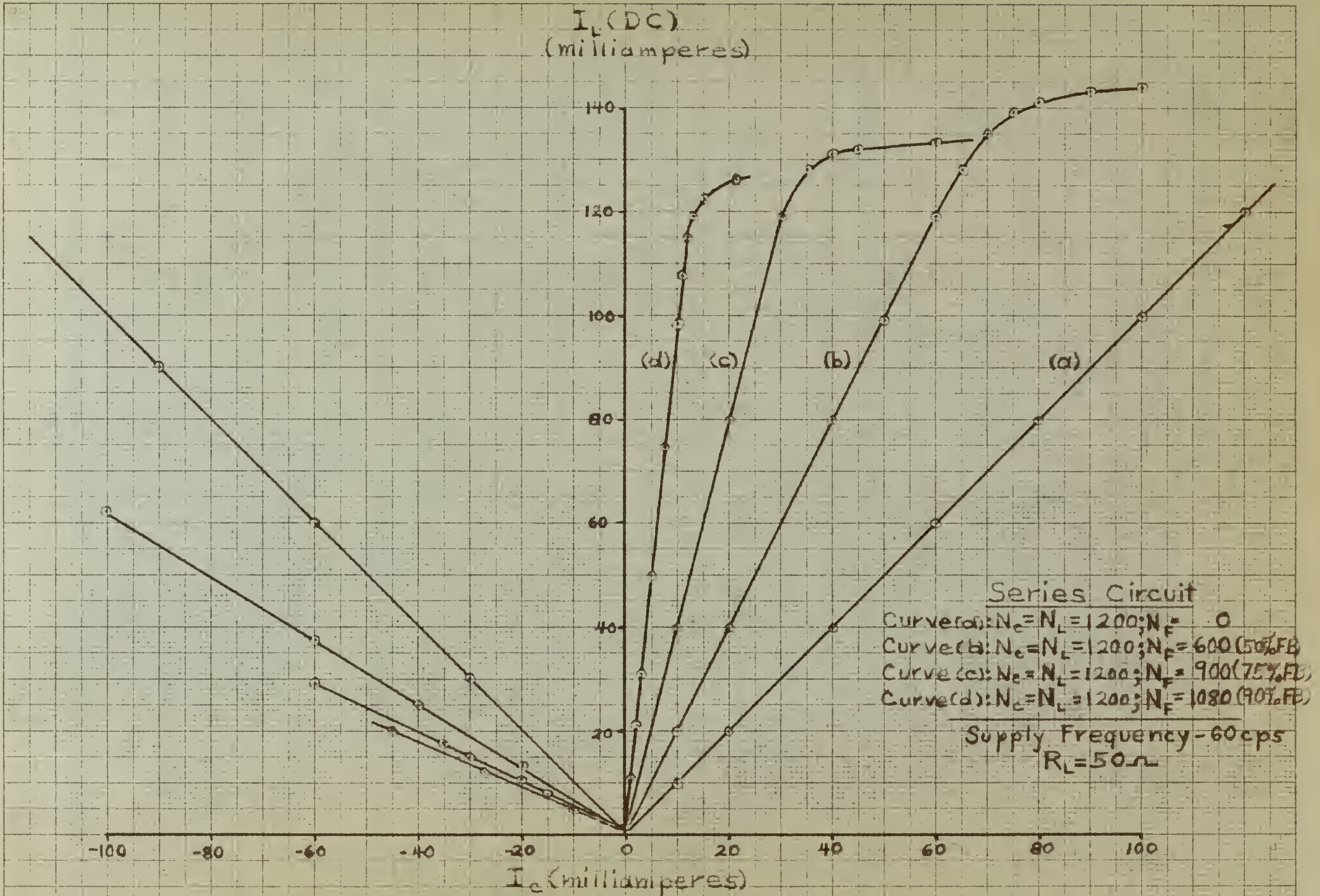

I_L (DC)
(milliamperes)
140
120
100
80
60
40
20
-100
-80
-60
-40
-20
0
20
40
60
80
100
I_e (milliamperes)
(a)
(b)
(c)
(d)
Series Circuit
Curve(a): N_c=N_L=1200; N_F= 0
Curve(b): N_c=N_L=1200; N_F=600(50%FB)
Curve(c): N_c=N_L=1200; N_F=900(75%FB)
Curve(d): N_c=N_L=1200; N_F=1080(90%FB)
Supply Frequency - 60 cps
R_L=50Ω

Figure 22

Series Circuit With Positive Feedback

Curve (b) of Figure 22 is the characteristic curve of the series circuit with 50% feedback. The circuit is shown in Figure 13. In this case, $N_L = N_C = 1200$, and $N_F = 600$. Therefore the value of feedback is $\frac{N_F}{N_L} \times 100 = 50\%$. This curve also is linear, and its slope is equal to the theoretical value, $\frac{N_C}{N_L}\left[\frac{1}{1-\frac{N_F}{N_L}}\right] = 2.$

Curve (c) of Figure 22 was made for the same circuit, with N_F increased to 900 Turns. The feedback is 75%, and the slope of the characteristic agrees with the theoretical value of 4.

Curve (d) represents the series circuit with 90% feedback. The slope is 10, and the results correspond with theoretical values.

It should be noted that with no feedback effect, the characteristic is symmetrical about the zero control current line, and that there is a small value of I_L at $I_C = 0$, due to the fact that the impedance of the load windings at this point is high but not infinite. As the feedback is increased, the characteristic crosses the $I_C = 0$ line at higher values of I_L, and reaches a minimum value at increasingly greater negative values of I_C. The slope to the left of the minimum I_L is decreased as feedback is increased.

Determining Greatest Stable Feedback

When N_F is increased to 1200 turns, the circuit is operating at 100% feedback. Curve (a) of Figure 23 is the characteristic for this case; it is seen that the slope is fairly constant over a considerable range but has not reached the theoretical infinite value.

For maximum gain, the turns in the feedback winding are greater by a small percentage than those in the power winding. The

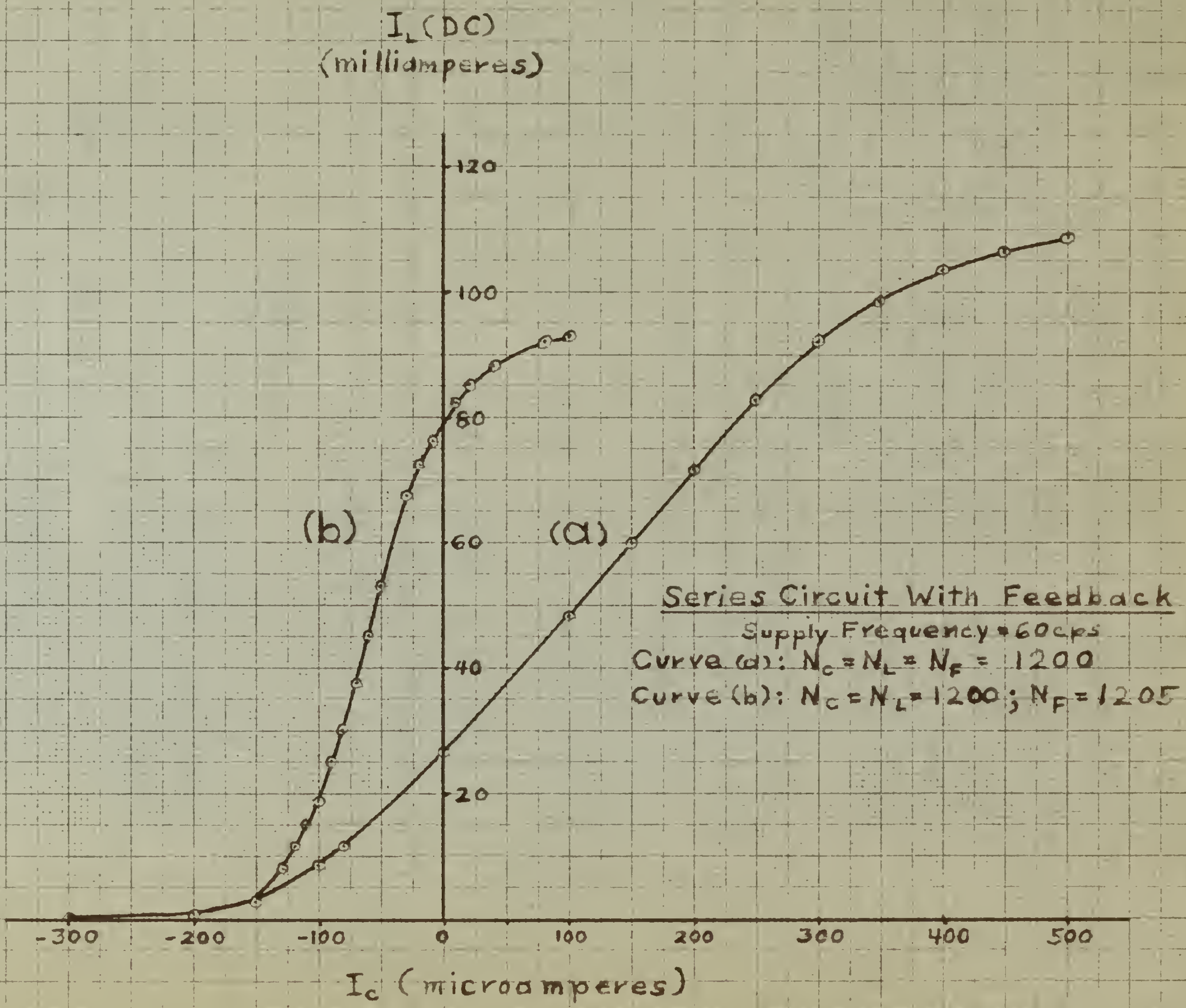

I_L (DC)
(milliamperes)
120
100
80
60
40
20
-300
-200
-100
0
100
200
300
400
500
I_c (microamperes)
(b)
(a)
Series Circuit With Feedback
Supply Frequency = 60cps
Curve (a): $N_c = N_L = N_F = 1200$
Curve (b): $N_c = N_L = 1200$; $N_F = 1205$

Figure 23

ratio $\frac{N_F}{N_L}$ is very critical. A change of one turn in several hundred greatly alters the power gain and conditions of stability. In this circuit it was possible to raise N_F to 1205 turns, and the amplifier was still stable. This is shown as curve (b) in Figure 23. When N_F was made 1206 turns, the amplifier became unstable. The extra turns above 1200 make up for losses in the rectifiers.

Adjusting Circuit for Maximum Gain

Making full use of the windings available on the cores, it was possible to increase the control turns to 2000, while the power turns were left at 1200 and the feedback turns at 1205. This combination gave the results plotted as curve (a) in Figure 24, and represents the maximum power gain obtained with this amplifier at 60 cycles.

The power gain of a magnetic amplifier is defined as the ratio of the change in power supplied to the load to the change in power dissipated in the control winding. That is:

$$\text{Power gain} = \frac{(\Delta I_L)^2 R_L}{(I_C)^2 R_C} .$$

Computing the power gain for the amplifier circuit whose characteristic curve is curve (a) in Figure 24, for the working range $-60\,\mu a < I_C < -10\,\mu a$, we have:

$\Delta I_L = (67 - 13) \times 10^{-3} = 54 \times 10^{-3}$ amperes

$R_L = 50$ ohms

$\Delta I_C = 50 \times 10^{-6}$ amperes

$R_C = 52$ ohms.

$$\therefore \text{Power gain} = \frac{(54)^2}{(50)^2} \times \frac{50}{52} \times 10^6 = 1.12 \times 10^6$$

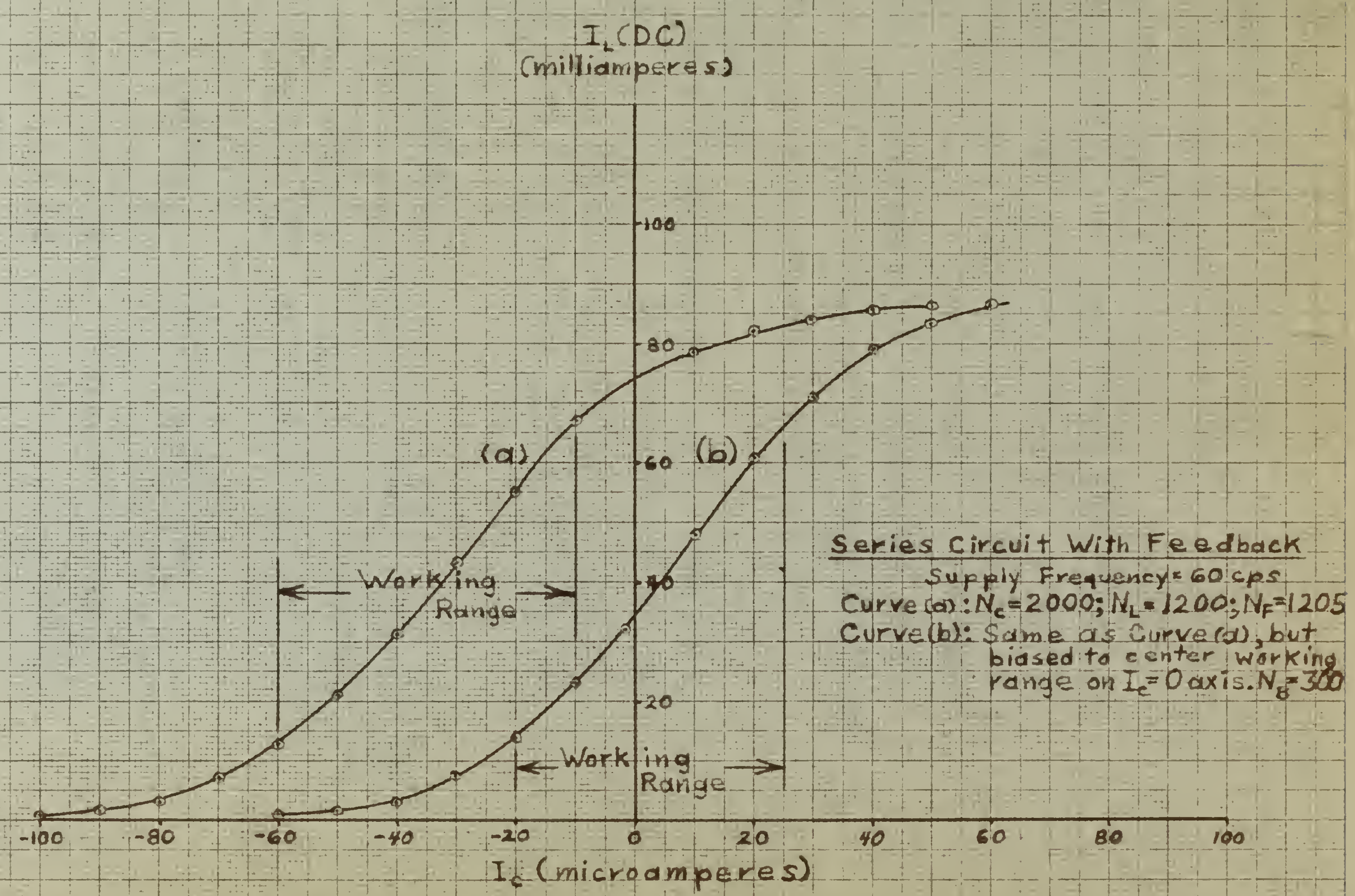

I_L (DC)
(milliamperes)
100
80
60
40
20
(a)
(b)
Working Range
Working Range
-100
-80
-60
-40
-20
0
20
40
60
80
100
I_c (microamperes)
Series Circuit With Feedback
Supply Frequency = 60 cps
Curve (a): $N_c = 2000$; $N_L = 1200$; $N_F = 1205$
Curve (b): Same as Curve (a), but biased to center working range on $I_c = 0$ axis. $N_B = 300$

Figure 24

Time Constant

An approximate measurement of the time constant for the maximum gain circuit was made by placing the voltage across the load on an oscilloscope, and observing the time taken for the load voltage to build up to 63% of its final value. The time elapsed was measured to be about 3 1/3 seconds; that is, the amplifier had a time delay of about 200 cycles, using 60 cycles per second supply frequency. As indicated by Figure 17, this delay can be decreased by increasing the resistance in the input circuit, or by reducing the number of feedback turns.

Biased Amplifier

By passing d-c current from a separate source controlled by a potentiometer, through 300 turns on each core, the amplifier was biased so that the operating range of the amplifier was centered on the line $I_C = 0$. This circuit is plotted as curve (b) in Figure 24.

Self-Saturated Circuit

Figure 25 is the characteristic curve for the parallel circuit with self-saturation shown in Figure 16. In this circuit, $N_C = 1200$, $N_L = 2400$, and $N_F = 0$. The results obtained were similar to those for the series circuit with $N_F = N_L$.

Tests Using 400 Cycles per Second Supply Frequency

The same procedure was used for determining the characteristics of magnetic amplifiers utilizing a supply frequency of 400 cycles per second as was followed for 60 cycles per second.

Operating Voltage

From Figure 26, the proper operating voltage was deter-

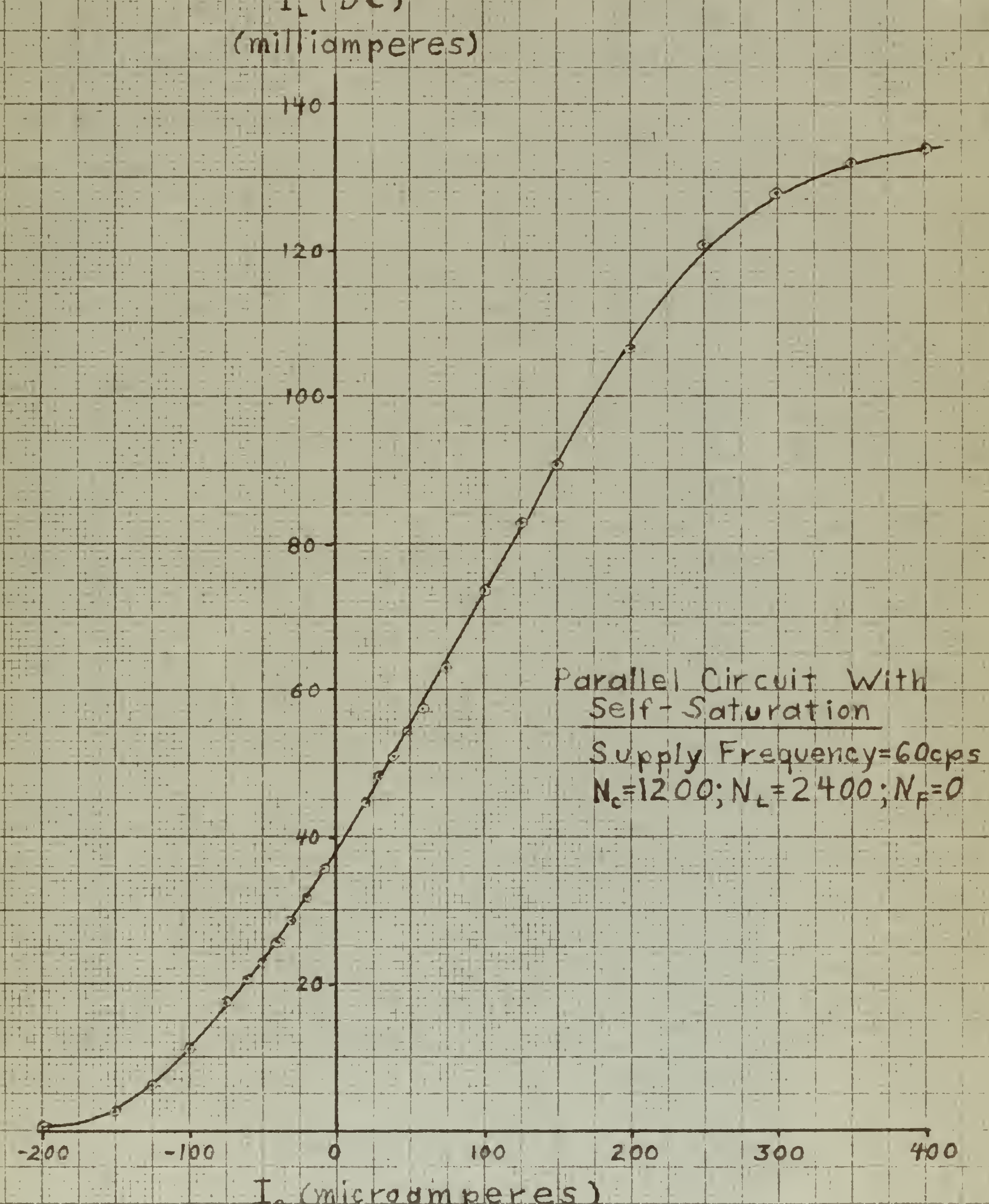

I_L (DC)
(milliamperes)
140
120
100
80
60
40
20
-200
-100
0
100
200
300
400
I_c (microamperes)
Parallel Circuit With Self-Saturation
Supply Frequency=60cps
N_c=1200; N_L=2400; N_F=0

Figure 25

Series Circuit Without Feedback

Variation of Load Current with 400 cps Supply Voltage

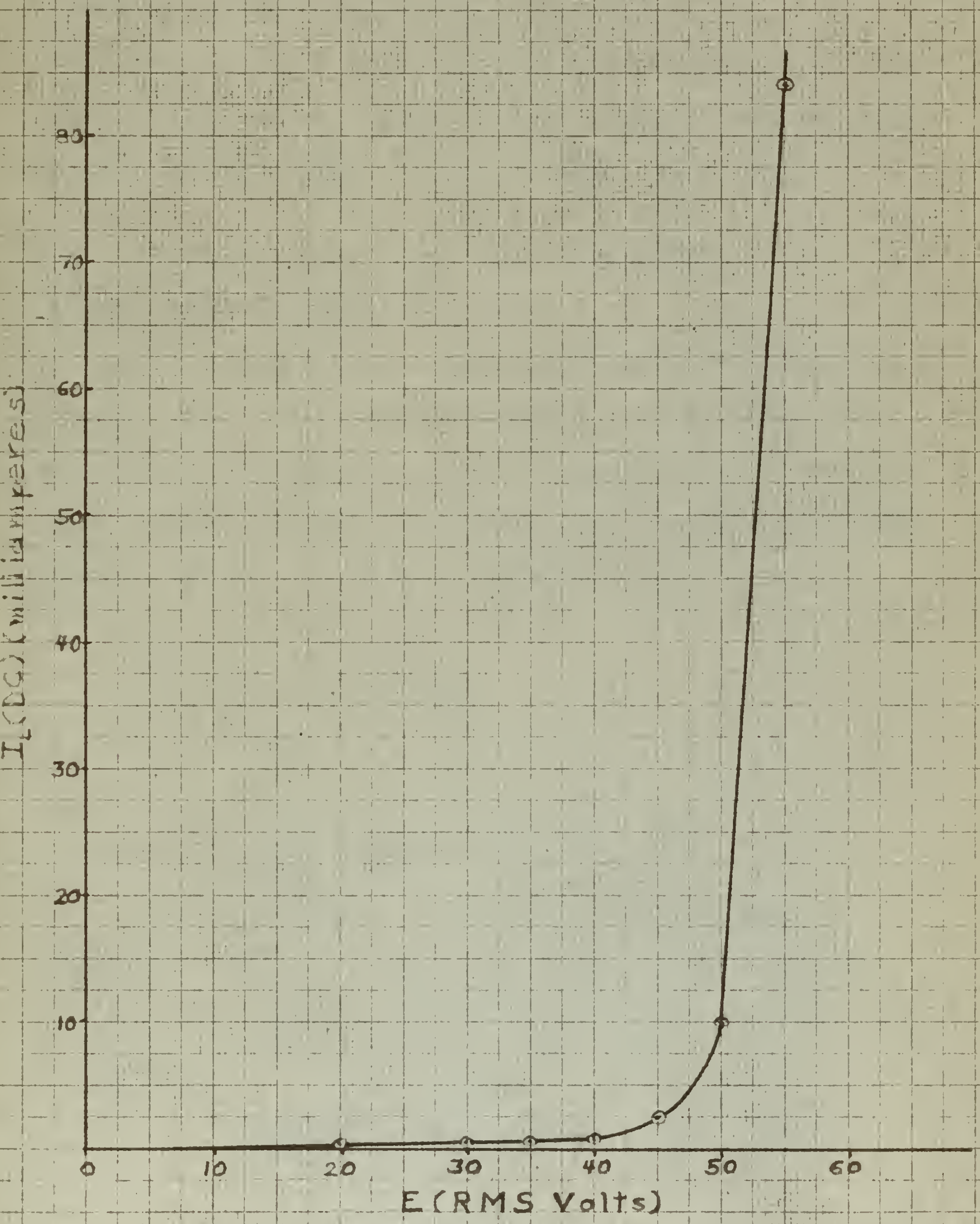


Figure 26

mined to be 45 volts.

Series Circuit

Figure 27 shows that the theoretical slopes were obtained, and the characteristic curves linear over the operating range, for no feedback and 50% feedback, with $N_C = N_L = 400$.

Figure 28 is a plot of the characteristics of an amplifier with $N_C = 3600$, $N_L = 400$, and $N_F = 200$ (50% feedback.) The theoretical slope should be $\frac{N_c}{N_L}\left[\frac{1}{1-\frac{N_F}{N_L}}\right] = \frac{3600}{400}\left[\frac{1}{\frac{1}{2}}\right] = 18.$ This is the actual slope of the curve in Figure 27.

Adjusting Turns for Highest Power Gain

Figure 29 shows the characteristic curves for $N_C = 3600$, $N_L = 400$, and $N_F = 400$ turns (100% feedback), and the increase in slope obtained by adding two additional feedback turns. An additional feedback turn made the amplifier unstable. The power gain, computed over the range, $195\,\mu a < I_c < 230\,\mu a$, is:

$\Delta I_C = 35 \times 10^{-6}$ amperes

$\Delta I_L = 270 \times 10^{-3}$ amperes

$R_L = 50$ ohms

$R_C = 80$ ohms

$$\therefore \text{Power gain} = \frac{(270)^2(50)}{(35)^2(80)} \times 10^6 = 37.1 \times 10^6 .$$

Thus the maximum power gain using 400 cycle supply is $\frac{37.1 \times 10^6}{1.12 \times 10^6} = 33.1$ times that at 60 cycles. The ratio $\left(\frac{N_c}{N_4}\right)400\sim$ is greater than $\left(\frac{N_c}{N_L}\right)60\sim$, and accounts roughly for the higher gain, as shown below:

$$\frac{\text{Gain } 400\sim}{\text{Gain } 60\sim} = \left[\frac{\left(\frac{N_c}{N_L}\right)_{400\sim}}{\left(\frac{N_c}{N_L}\right)_{60\sim}}\right]^2 = \left[\frac{9}{\frac{5}{3}}\right]^2 = 29.16 .$$

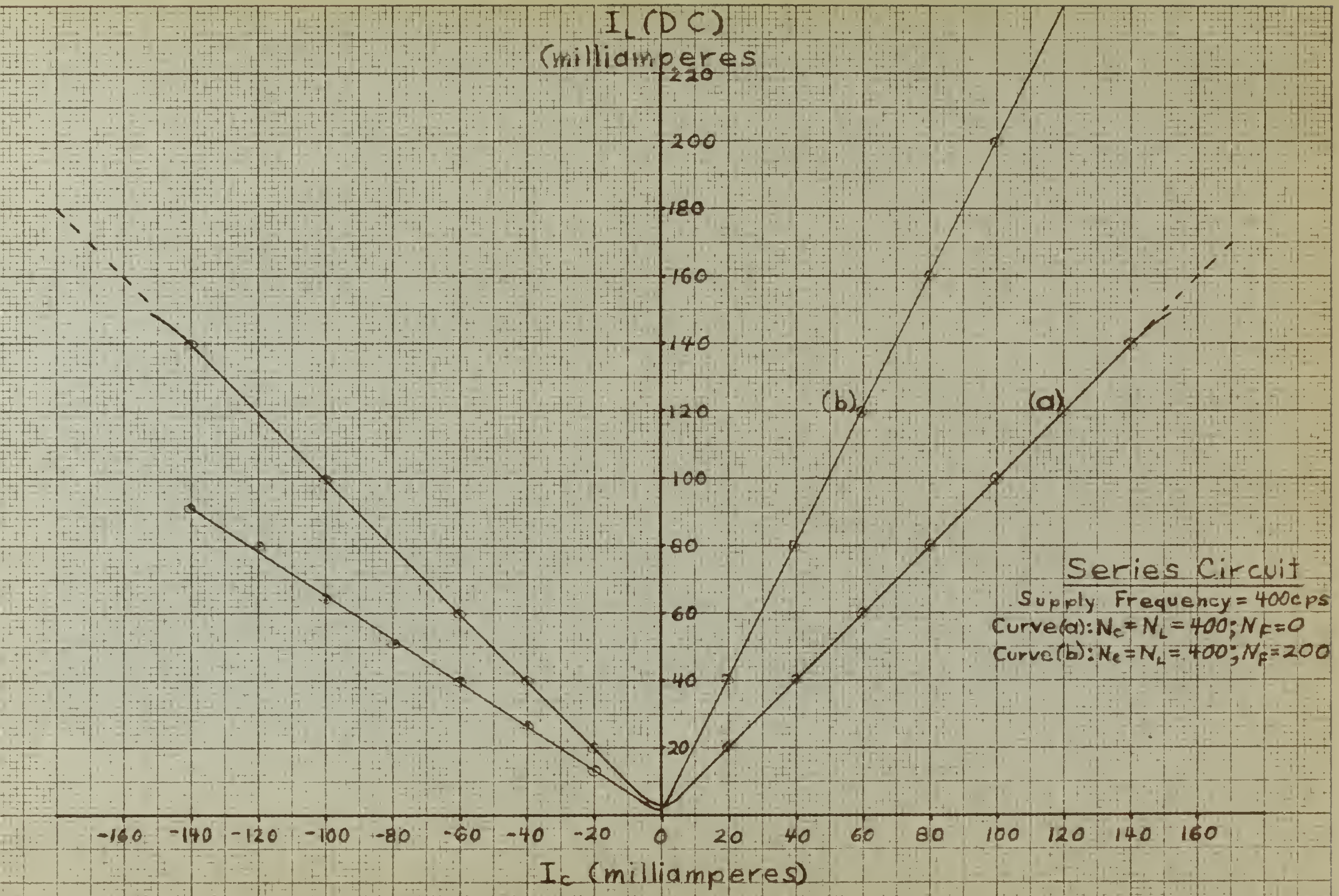

I_L (DC)
(milliamperes
220
200
180
160
140
120
100
80
60
40
20
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
I_c (milliamperes)
(b)
(a)
Series Circuit
Supply Frequency = 400cps
Curve(a): $N_c = N_L = 400; N_F = 0$
Curve(b): $N_c = N_L = 400; N_F = 200$

Figure 27

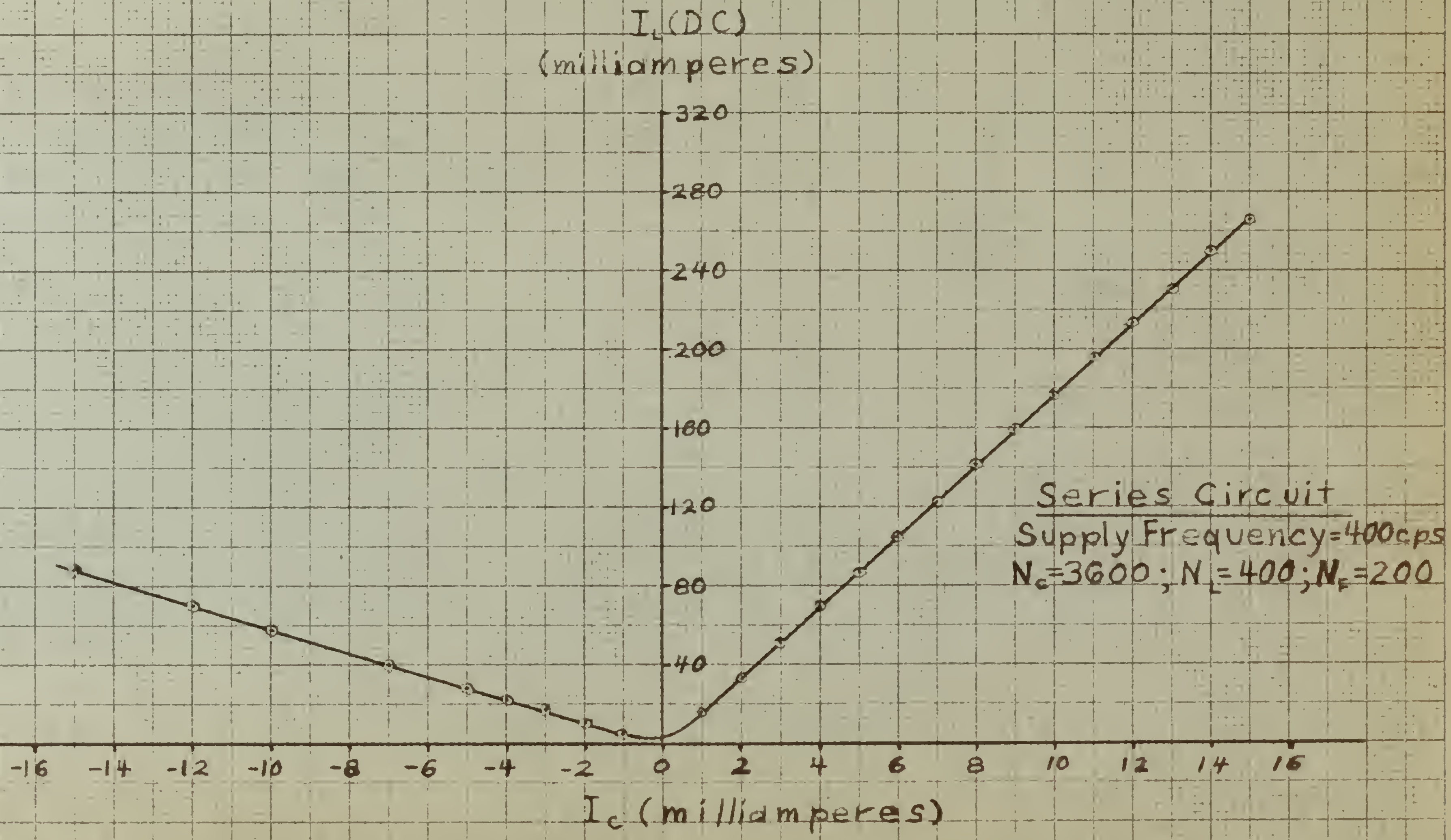

I_L(DC)
(milliamperes)
320
280
240
200
160
120
80
40
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
14
16
I_c (milliamperes)
Series Circuit
Supply Frequency=400cps
N_c=3600; N_L=400; N_F=200

Figure 28

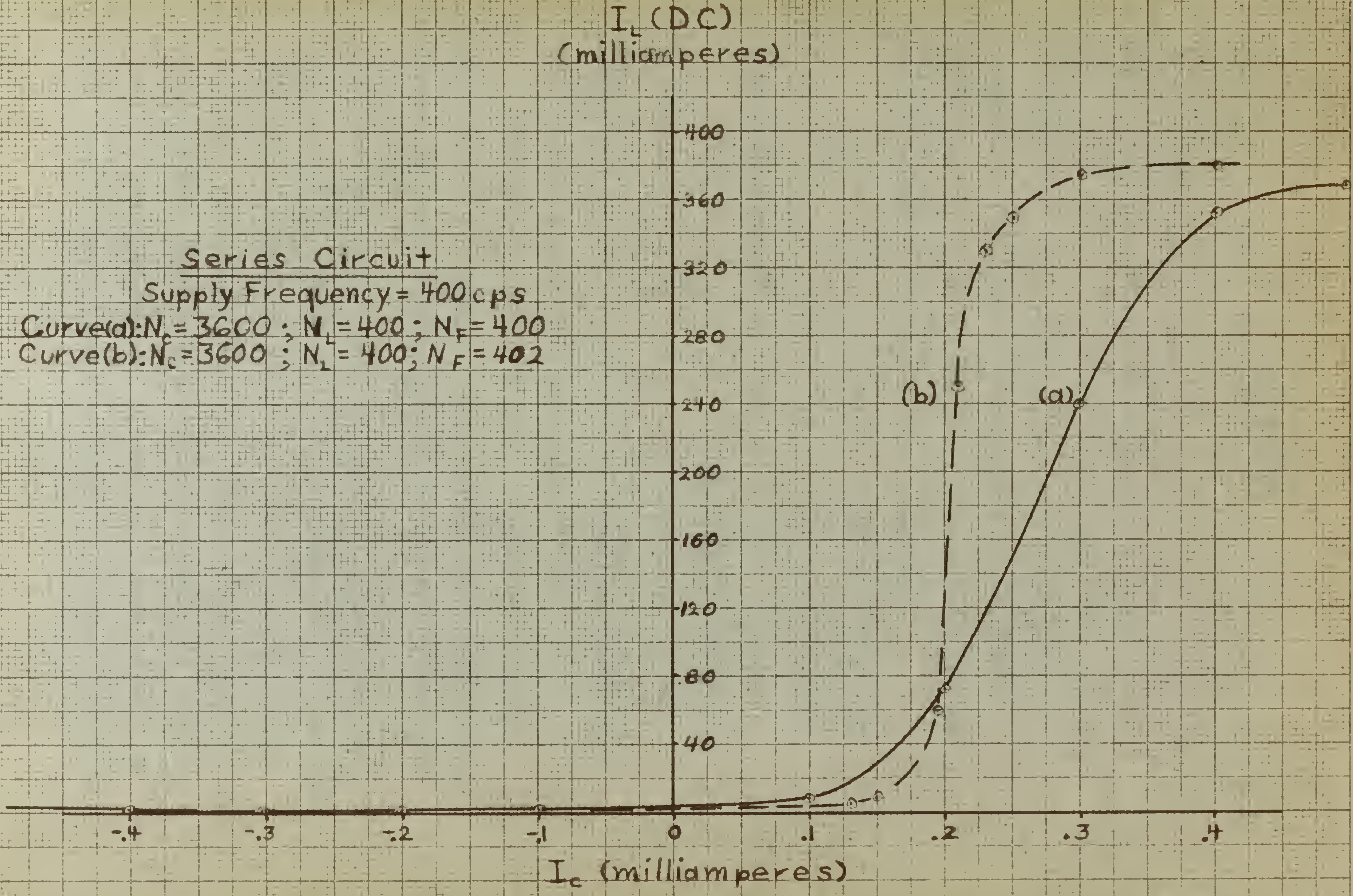

I_L (DC)
(milliamperes)
400
360
320
280
240
200
160
120
80
40
0
-.4
-.3
-.2
-.1
.1
.2
.3
.4
I_c (milliamperes)
(a)
(b)
Series Circuit
Supply Frequency = 400 cps
Curve(a): $N_c = 3600$; $N_L = 400$; $N_F = 400$
Curve(b): $N_c = 3600$; $N_L = 400$; $N_F = 402$

Figure 29

CONCLUSIONS

Various types of core materials for magnetic amplifiers are available; the factors determining which material is best suited for a particular application are: signal power available, overall gain required, power output required, and the size and weight of the amplifier. For the purposes of this essay, Mu Metal was chosen since it provides the largest power gain, and requires relatively low ampere turns for saturation.

In the series circuit with no feedback, the tests made show that the relationship between I_L and I_C over the working range of the amplifier is linear, and is: $\frac{I_L}{I_C} = \frac{N_C}{N_L}$.

When positive feedback is introduced, this relationship is changed to: $\frac{I_L}{I_C} = \frac{N_C}{N_L} \cdot \frac{1}{1 - \frac{N_F}{N_L}}$. This expression hold for feedbacks up to 90%; the measured values of $\frac{I_L}{I_C}$ corresponded exactly to those given by this ampere-turns balance.

The maximum power gain for an amplifier is obtained by adding additional feedback turns above 100%, where feedback is defined as $\frac{N_F}{N_L}$, until the amplifier becomes unstable. The greatest number of feedback turns permitting stable operation of the amplifier provides the highest gain. This procedure is not recommended for practical purposes, however, as the turns over 100% feedback make up for losses in the rectifier, which change with temperature and age, and an amplifier which is stable under one set of testing conditions may become unstable when the temperature changes. For this reason, in most practical applications, feedback over 100% is

not used, but instead, two or more stages of amplification are used to provide a consistent, very high power gain. In this study, however, the object was to achieve the maximum power gain in one stage. The results obtained were a power gain of 1.12×10^6 using a supply frequency of 60 cycles per second, and 37.1×10^6 using a supply frequency of 400 cycles per second. Under the maximum gain conditions, the time delay of the amplifier was 200 cycles of the supply frequency.

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VITA

James Pollock Jamison was born in Pittsburgh, Pennsylvania, on June 6, 1918. He graduated from Dormont High School, Dormont, Pennsylvania, in 1935 and that same year entered the Carnegie Institute of Technology, pursuing a course in aeronautical engineering for two years. In 1937 he was appointed to the United States Naval Academy at Annapolis, Maryland, graduating in 1941 with the degree of Bachelor of Science, and was commissioned an ensign in the United States Navy. He served in various naval vessels, was commissioned a lieutenant commander in 1945, and in 1947 entered the U. S. Naval Postgraduate School in a course in the Guidance of Guided Missiles. In 1948 he was transfered to The Johns Hopkins University at Baltimore, Maryland, for two years, to complete that course in the Department of Electrical Engineering.

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